Fermi Transients and Multimessenger Observations

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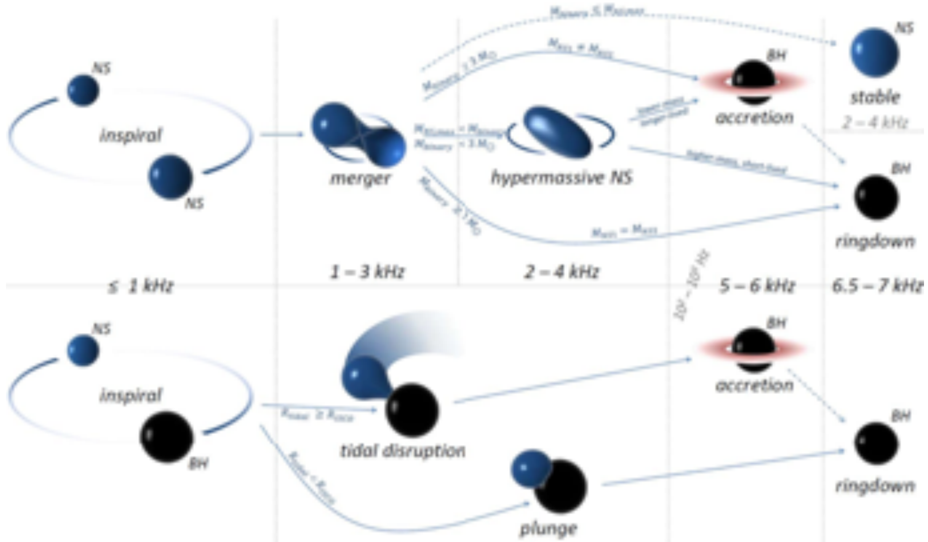
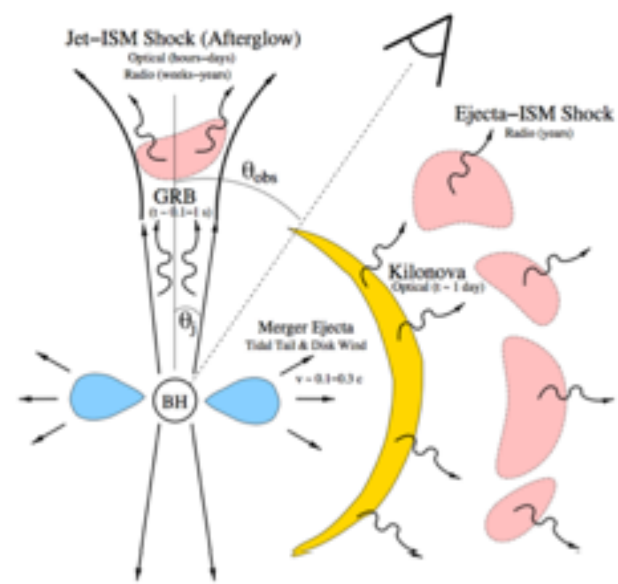
Short GRBs as Gravitational Wave Counterparts

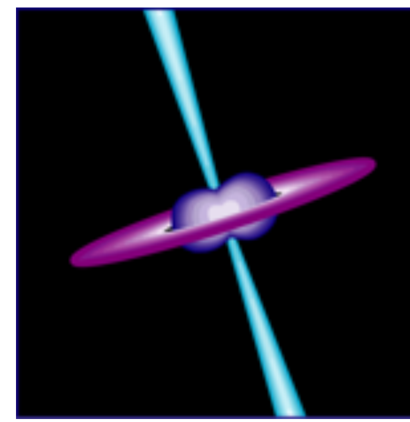
- NS-NS & NS-BH mergers should produce a GRB
  - detected if jet is pointed towards Earth (on axis)
- merging compact objects produce GWs
  - we know this for sure from LIGO/Virgo
- If short GRBs are within LIGO detection range and pointed towards Earth, we should see gamma rays & GWs concurrently
- Short GRBs are rare, and LIGO NS-NS range at design sensitivity (2020) is expected to be 200 Mpc (sky and orientation averaged)
  - increases a bit for those on-axis
  - short GRB detection can push GW threshold lower and range higher





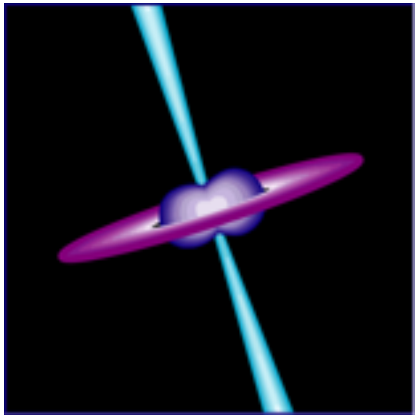
Short GRB/GW Rates

- short GRB rates come from gamma-ray observations (inherently accounts for beaming)
  - ~10±5 Gpc^{-3} yr^{-1} (Guetta and Piran 2006; Nakar et al. 2006; Guetta & Stella 2009, Coward et al. 2012, Wanderman & Piran 2015, Ghirlanda et al. 2016)
- 200 Mpc NS-NS merger range distance (400 Mpc - NS+10 $M_\odot$ BH)
  - (GW volume)*(Rate/vol) -> 0.34 ± 0.17 sGRBs yr^{-1}
- Enhanced GW amplitude along jet axis - range x 1.5
  - -> 1.13 ± 0.57 sGRBs yr^{-1}
- Coincident prompt signal pushes GW threshold lower - range x 1.5 (Cutler and Thorne 2002)
  - NS-NS rate: 3.8 ±1.7 sGRBs yr^{-1} (all sky)
  - NS-BH rate: 30 ±15 sGRBs yr^{-1} (all sky)
- Scale total rate by fraction of sky covered by instrument field of view and sensitivity
- GW duty cycle



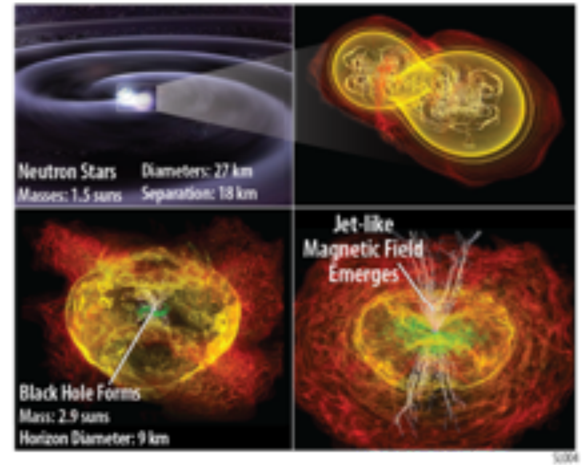
Alternative Short GRB/GW Rates

- NS-NS merger rates from GW observations of GW170817
  - 1540 {-1220,+3200} Gpc^{-3} yr^{-1} (Abbott et al. 2017)
  - assume same for NS-BH (total speculation)
- sGRB jet opening half-angle 15-30 deg (Fong et al. 2015) - assume 20 deg
  - 1-cos(20) = 0.06
- 200 Mpc NS-NS merger range distance (400 Mpc - NS+10 $M_\odot$ BH) -> (GW volume)*(1-cos θ)(Rate/vol)
  - 3.1 {-2.5,+12.7) sGRBs yr^{-1} (NS-NS)
  - 25 {-20,+100) sGRBs yr^{-1} (NS-BH)
- Enhanced GW amplitude along jet axis - range x 1.5
  - 10.5 {-8,+43} sGRBs yr^{-1} (NS-NS)
  - 84 {-67,+344} sGRBs yr^{-1} (NS-BH)
- Coincident prompt signal pushes GW threshold lower - range x 1.5 (Cutler and Thorne 2002)
  - NS-NS rate: 35.5 {-28,+145} sGRBs yr^{-1} (all sky)
  - NS-BH rate: 283 {-225,+1160} sGRBs yr^{-1} (all sky)
- Scale total rate by fraction of sky covered by instrument field of view, sensitivity, GW duty cycle
- Gamma-ray horizon?



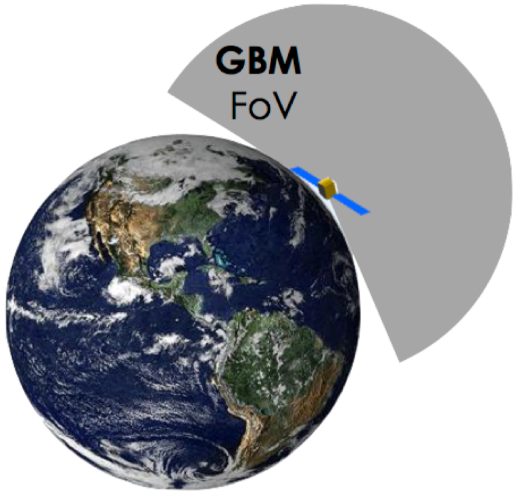
How to optimize GRB/GW coincident observations?

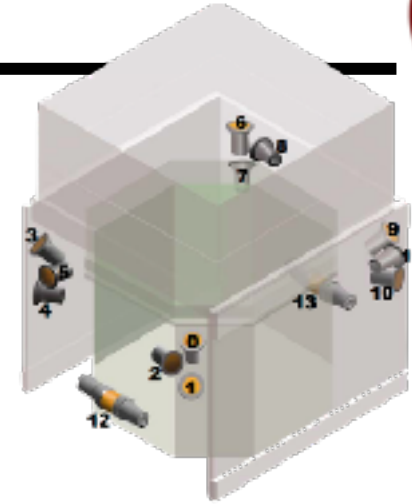
- **Need wide field of view instrument**
  - **detections = sky fraction in FoV * rate**
- **Need accurate absolute timing (to confirm coincidence)**
- **Need localization capability**
  - **spatial coincidence (though timing still useful)**
- **Need rapid trigger and location dissemination**
- **Need broad energy coverage with good sensitivity**
- **Need high rate of GRB detection**



- **Fermi**
  - **GBM is the most prolific detector of short GRBs**
  - **LAT detects afterglow emission from brightest/hardest short GRBs**
  - **LAT is the only instrument capable of searching for GRB afterglows <u>all-sky</u> in reasonable timeframe (~hours), without changing observing strategy**

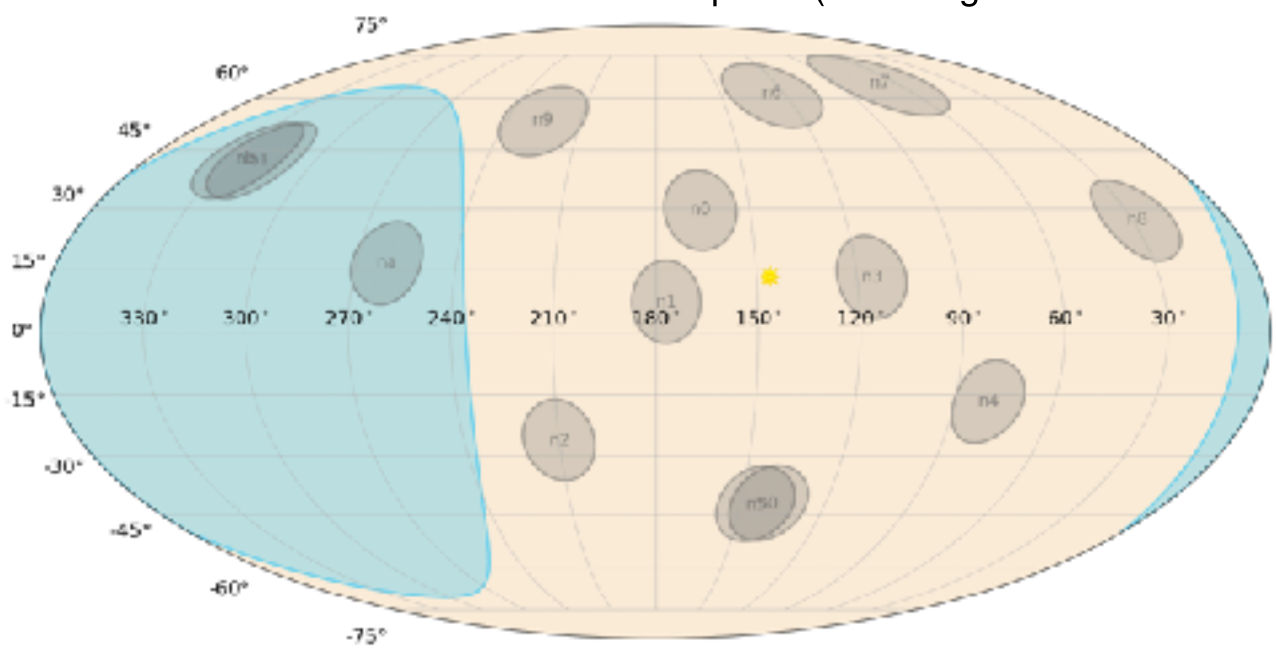
GBM Sky Coverage





GBM instantaneous field of view: ~70% of the sky

~87% uptime (off during South Atlantic Anomaly)



GBM Triggers

Triggering algorithms:

- In-orbit count rate increase in 2+ NaI detectors above adjustable threshold above background (70 algorithms operating simultaneously)
    - between 4.5 and 7.5 sigma
    - 10 timescales — 16ms up to 8.096s
    - 4 energy ranges — [50-300], [25-50], >100, >300 keV
- Ground-based offline search for rate increase
- Long transients and persistent sources:
    - Earth occultation
    - Pulsar phase folding

GBM Data Products

https://fermi.gsfc.nasa.gov/ssc/data/access/gbm/

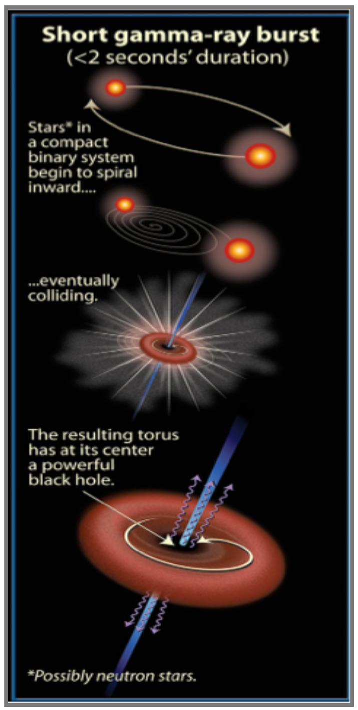
Data products:

- TRIGDAT, triggered data — mainly for localization and quick look
  - 1024/256/64 ms, 8 energy channels
- CTIME, continuous high time resolution → lightcurves
  - 256 (64) ms, 8 energy channels
- CSPEC, continuous high spectral resolution → spectral analysis
  - 4096 (1024) ms, 128 energy channels
- TTE / CTTE, time tagged events
  - 2µs, 128 energy channels → both!
  - Continuous TTE enabled Nov 2012, hourly files available

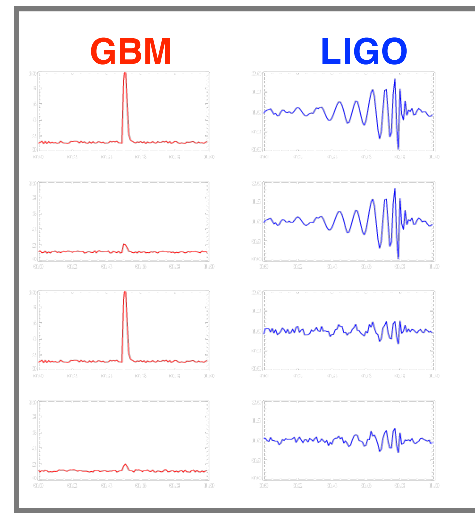
Offline GRB Search Pipelines

1. Untargeted search for subthreshold GRB candidate events

2. Targeted search using input event time and optional skymap



Ideal Scenario	Bright GBM	Bright LIGO
GW150914 Scenario	Sub-threshold GBM	Bright LIGO
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO

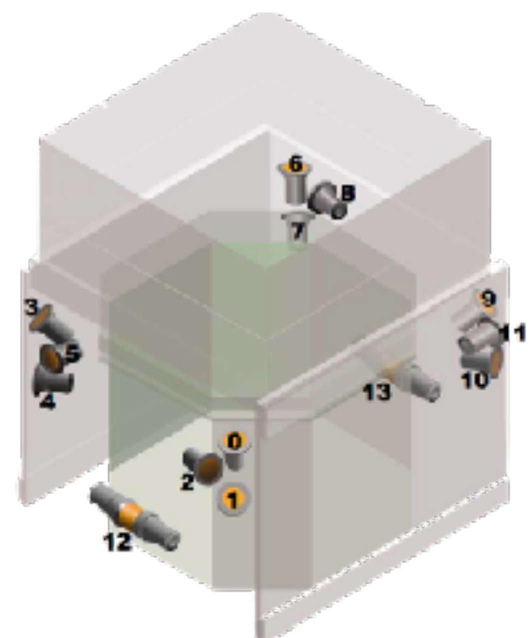


GBM Untargeted Search

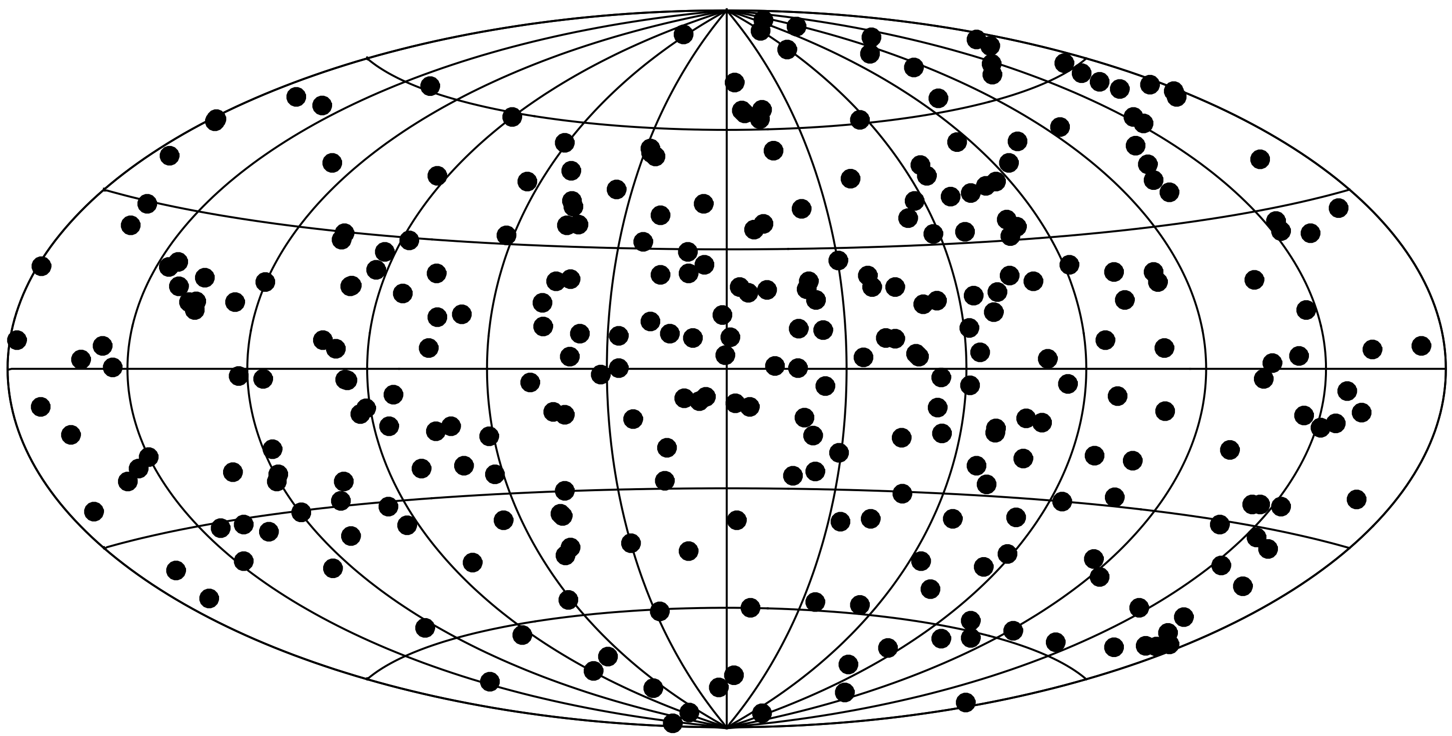
Extends the onboard trigger algorithms, with improved background model.

- Looks for signals in 2 NaI detectors with 2.5σ and 1.25σ excess above background in the continuous time-tagged events (2μs resolution, 128 energy channels).
- The 2 signal detectors must have valid geometry for a point source.
- **18 timescales: 64ms to 32s**.
  - Only candidates <2.8s are reported at the moment.
- **4 energy ranges** optimized for short GRBs.
  - 27—539 keV; 50—539 keV; 102—539 keV; 102—985 keV
- Expected rate of notice ~70/month, higher during active periods of galactic transients.

- From April 2017 to now, **64/month**, excluding Oct/Nov 2017
  - Found additional burst-like transients from magnetars and X-ray binaries, such as
    - AXP CXOU J164710.2-455216 / PSR J1647-4552
    - Swift J0243.6+61
- **GRB170817A: could dim x0.5 and still recover by untargeted search.**



GBM Untargeted Search



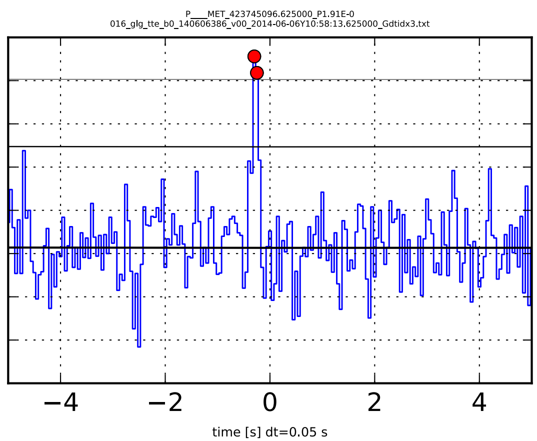
- 318 short, hard candidates found in 46 months in previous study.
  ➡ ~80 per year.

Candidate Event from Untargeted Search

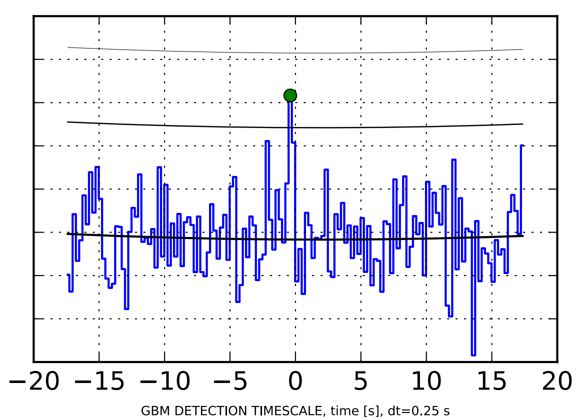
- **2014-06-06 10:58:13.625**
- **Swift GRB 140606A**
- **Found in 0.25s time binning**
- **93 - 494 keV energy range**

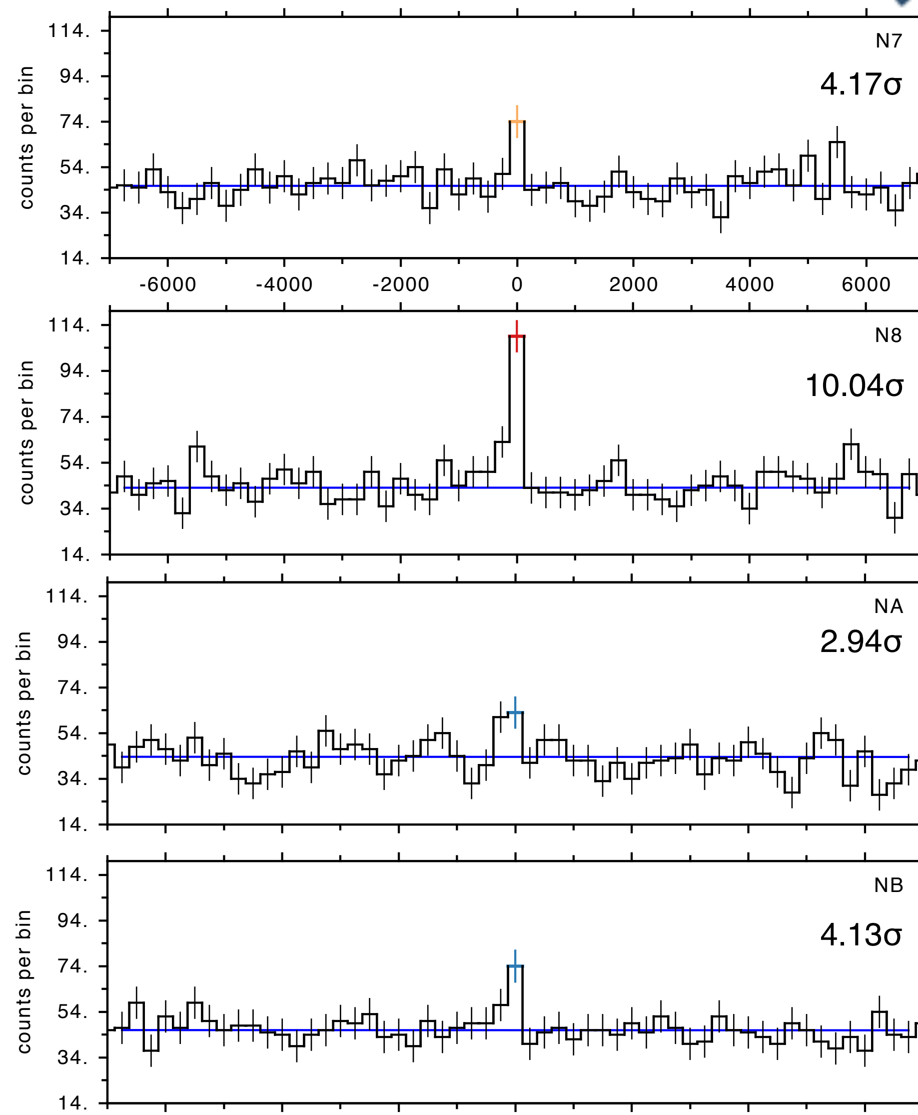
INTEGRAL ACS lightcurve

ACS native time bin



GBM timescale



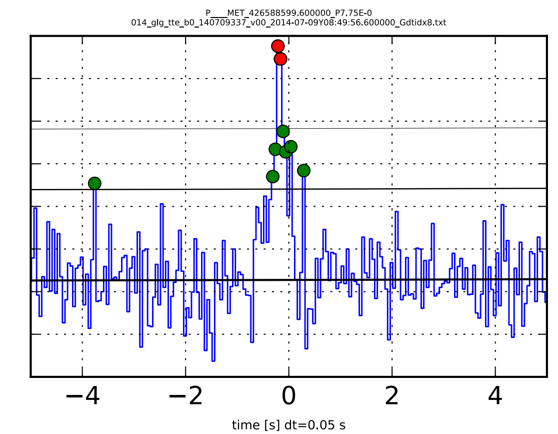


Candidate Event from Untargeted Search

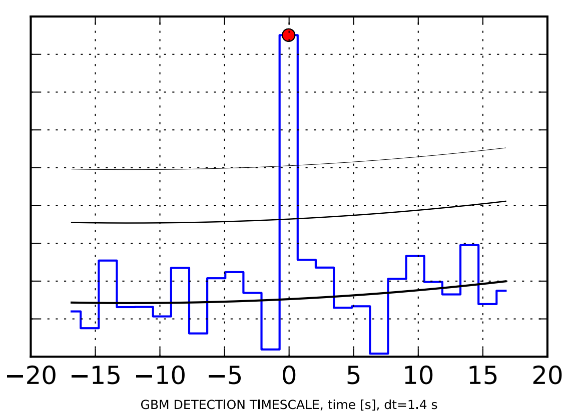
- **2014-07-09 08:49:56.600**
- **Found in 1.40s time binning**
- **25 - 494 keV energy range**

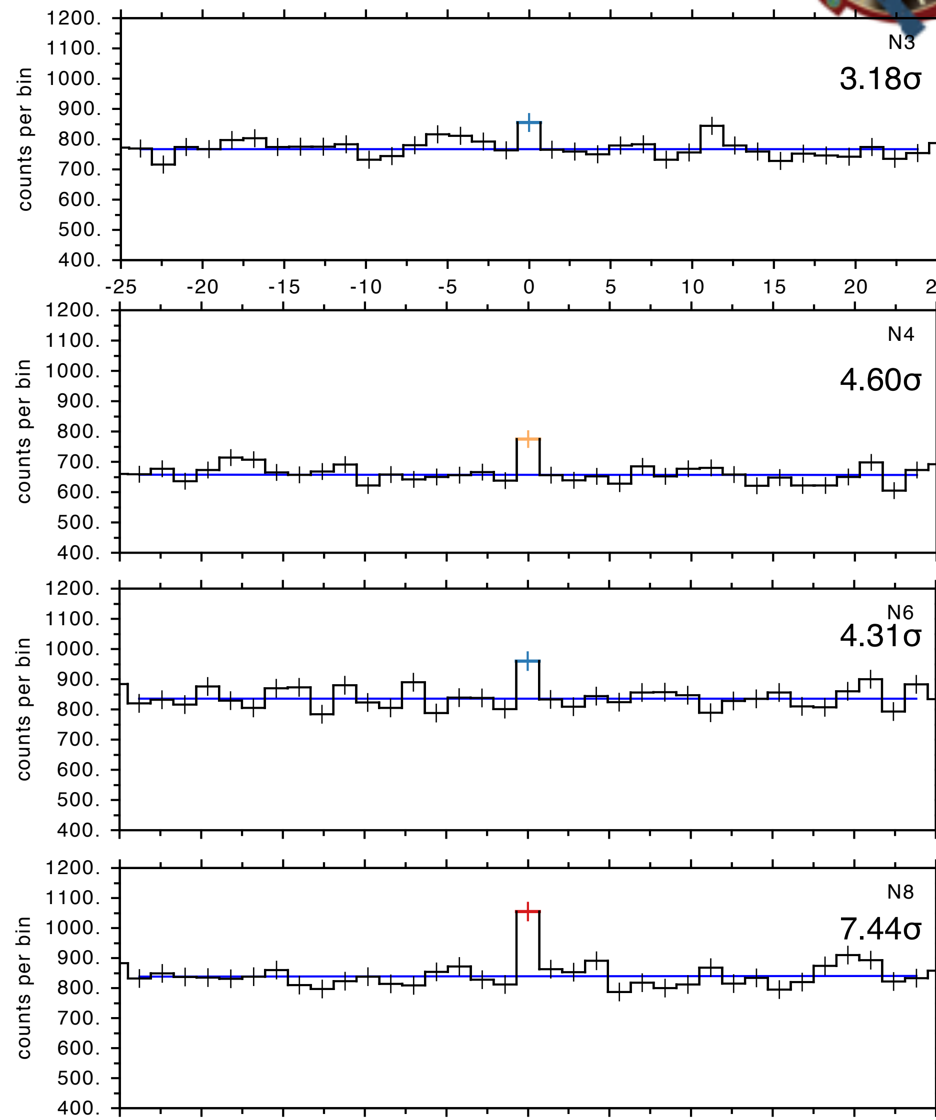
INTEGRAL Anti-Coincidence Shield(ACS) lightcurve

ACS native time bin



GBM timescale





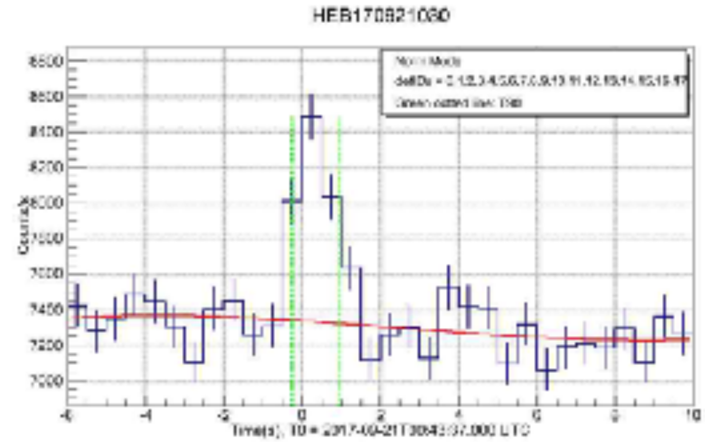
Candidate Event from Untargeted Search

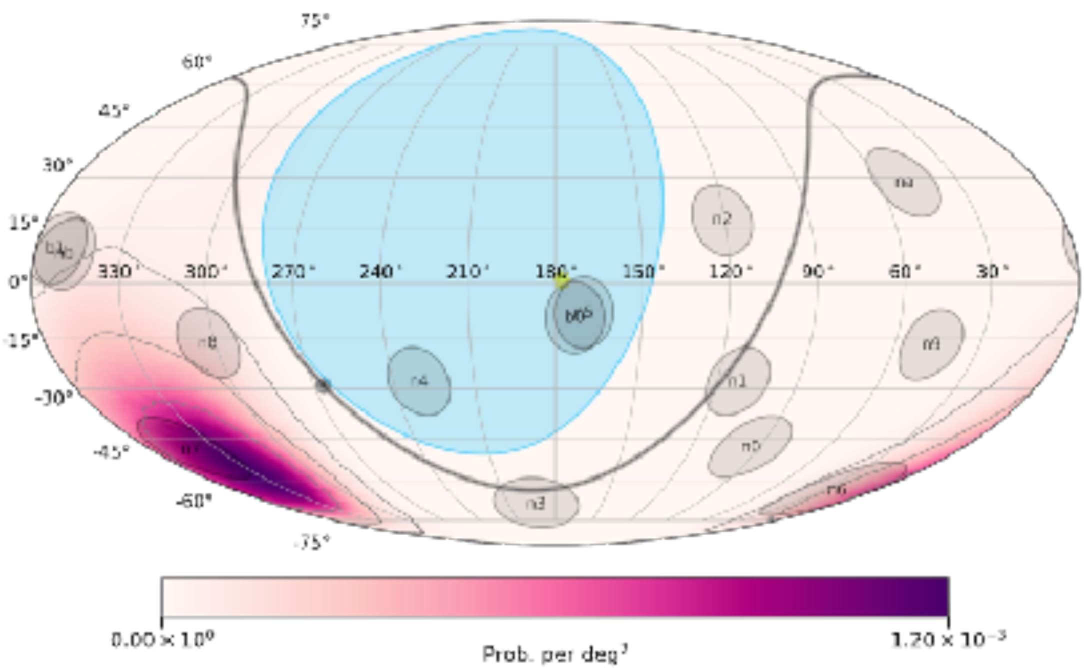
GRB 170921C [Zhang et al. GCN 21919]

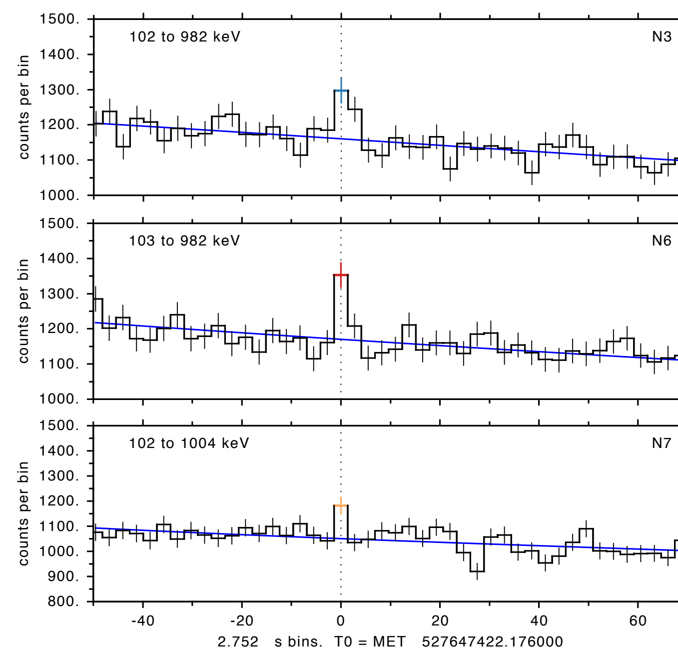
- Insight-HXMT 12σ detection coincident with Fermi-GBM subthreshold transient 527647422.
- T90 is 1.2s, energy range ~200-800 keV.

Fermi-GBM transient 527647422 info:

- High reliability candidate
- 3 detectors >4σ
- 2.8s long

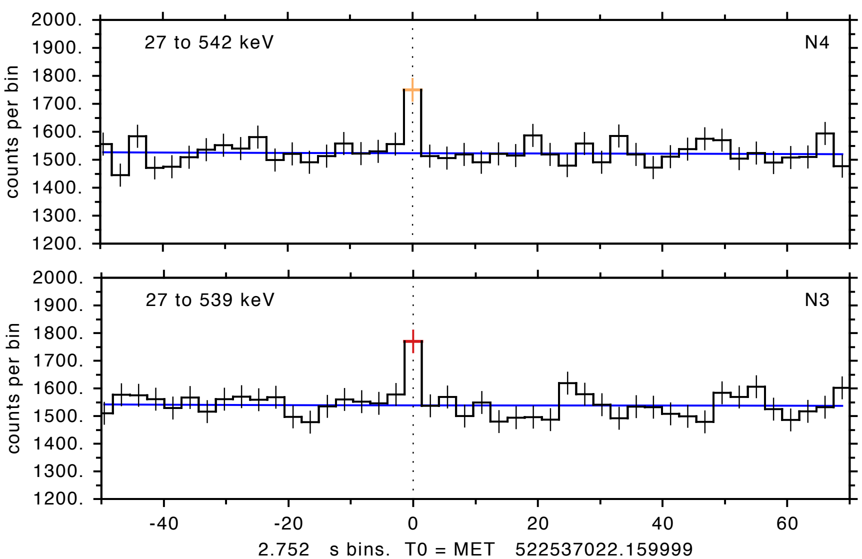


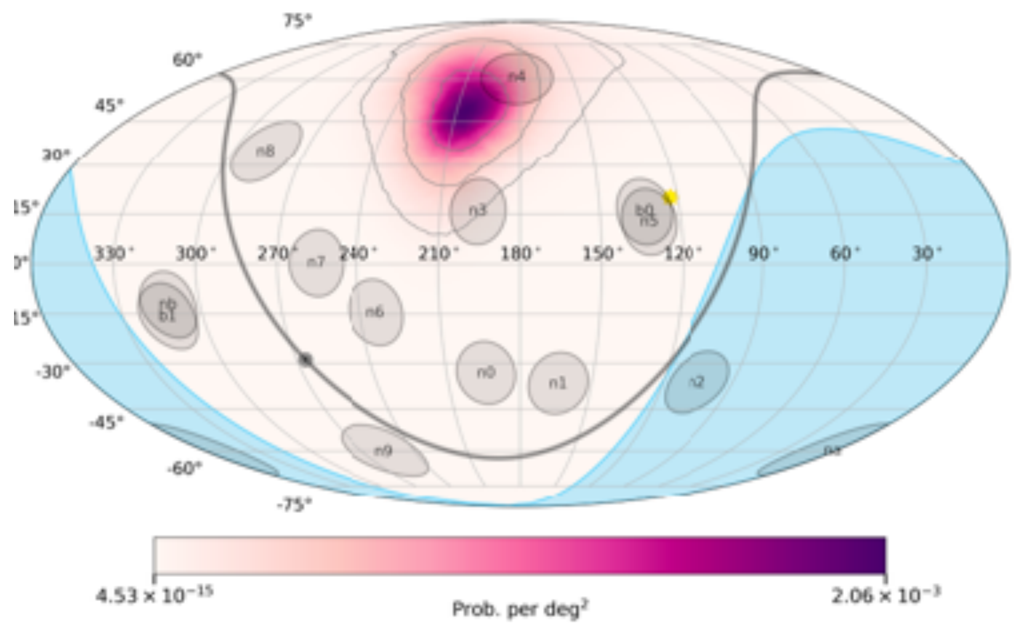




GBM Untargeted Search

- GCN notice type Fermi-GBM SubThreshold now available. https://gcn.gsfc.nasa.gov/fermi_gbm_subthreshold.html
- Time delay for notice range from 0.5 to 6 hours, due to telemetry schedule.
- List of candidates from older data (2013 and on) are available. http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html
- Available with the GCN notice:
  - Localization FITS file
  - Contour sky map
  - Lightcurve





GBM Untargeted Search

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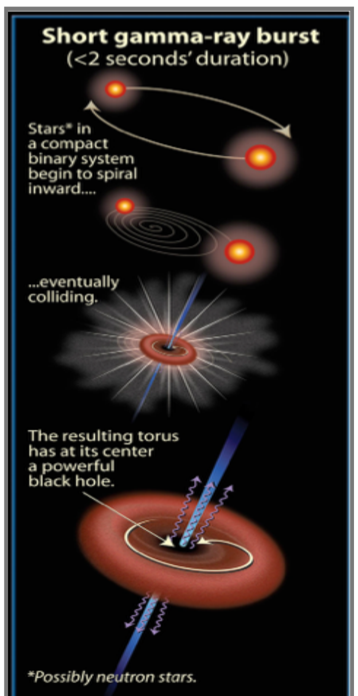
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/FERMI NOTICE
NOTICE_DATE:      Thu 21 Sep 17 03:15:48 UT
NOTICE_TYPE:      Fermi-GBM SubThreshold
TRANS_NUM:        527647422
FULL_ID_NUM:      527647422.176000
TRANS_RA:         341.610d {+22h 46m 26s} (J2000),
                  341.906d {+22h 47m 37s} (current),
                  340.768d {+22h 43m 04s} (1950)
TRANS_DEC:        -65.830d {-65d 49' 47"} (J2000),
                  -65.736d {-65d 44' 09"} (current),
                  -66.093d {-66d 05' 35"} (1950)
TRANS_ERROR:      17.08 [deg radius, stat+sys, 68% containment]
TRANS_DURATION:   2.751 [sec]
TRANS_DATE:       18017 TJD;    264 DOY;    17/09/21
TRANS_TIME:       2617.18 SOD {00:43:37.18} UT
EARTH_ANGLE:      120.59 [deg]
SPECTRAL_CLASS:   1     (0=soft, 1=hard)
TYPE_CLASS:       0     (0=short, 1=long)
RELIABILITY:      8     (2=low, 5=medium, 8=high)
HEALPIX_URL:      https://gcn.gsfc.nasa.gov/notices_gbm_sub/gbm_subthresh_527647422.176000_healpix.fits
MAP_URL:          https://gcn.gsfc.nasa.gov/notices_gbm_sub/gbm_subthresh_527647422.176000_map.png
LC_URL:           https://gcn.gsfc.nasa.gov/notices_gbm_sub/gbm_subthresh_527647422.176000_lc.pdf
SUN_POSTN:        178.48d {+11h 53m 54s}   +0.66d {+00d 39' 37"}
SUN_DIST:         113.85 [deg]   Sun_angle= -10.9 [hr] (East of Sun)
MOON_POSTN:       190.08d {+12h 40m 19s}   -0.26d {-00d 15' 37"}
MOON_DIST:        110.98 [deg]
MOON_ILLUM:       1 [%]
GAL_COORDS:       320.97,-46.68 [deg] galactic lon,lat of the burst (or transient)
ECL_COORDS:       308.91,-51.78 [deg] ecliptic lon,lat of the burst (or transient)
COMMENTS:         Fermi-GBM Subthreshold.
COMMENTS:         This Notice was ground-generated -- not flight-generated.
```

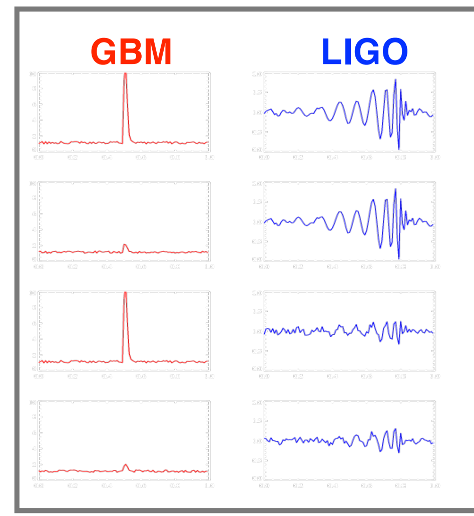
Offline GRB Search Pipelines

1. Untargeted search for subthreshold GRB candidate events

2. **Targeted search using input event time and optional skymap**

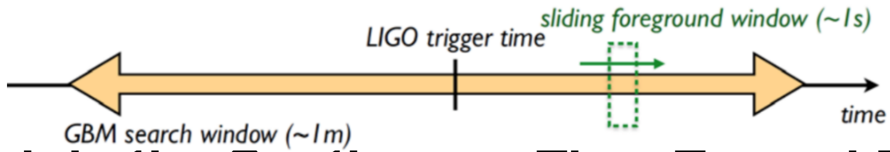


Ideal Scenario	Bright GBM	Bright LIGO
GW150914 Scenario	Sub-threshold GBM	Bright LIGO
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO



GBM Untargeted Search

Coherent search over GBM detectors



- **Targeted search in the Continuous Time Tagged Events (CTTE) data. (Blackburn et al. 2015, Goldstein et al. arXiv:1612:02395)**
  - **Looks for coherent signals in all detectors given an input time and optional skymap.**
  - **Calculate likelihood ratio of source and background.**
  - **Search +/- 30 seconds of input event time.**
  - **Sliding timescales from 0.256s to 8s (capable down to 0.064s) with a factor of 4 phase shift.**
  - **3 source spectral templates using Band function: soft, normal, and hard.**

background-subtracted counts; response; source amplitude

product over independent observations (detectors/ energy channels)

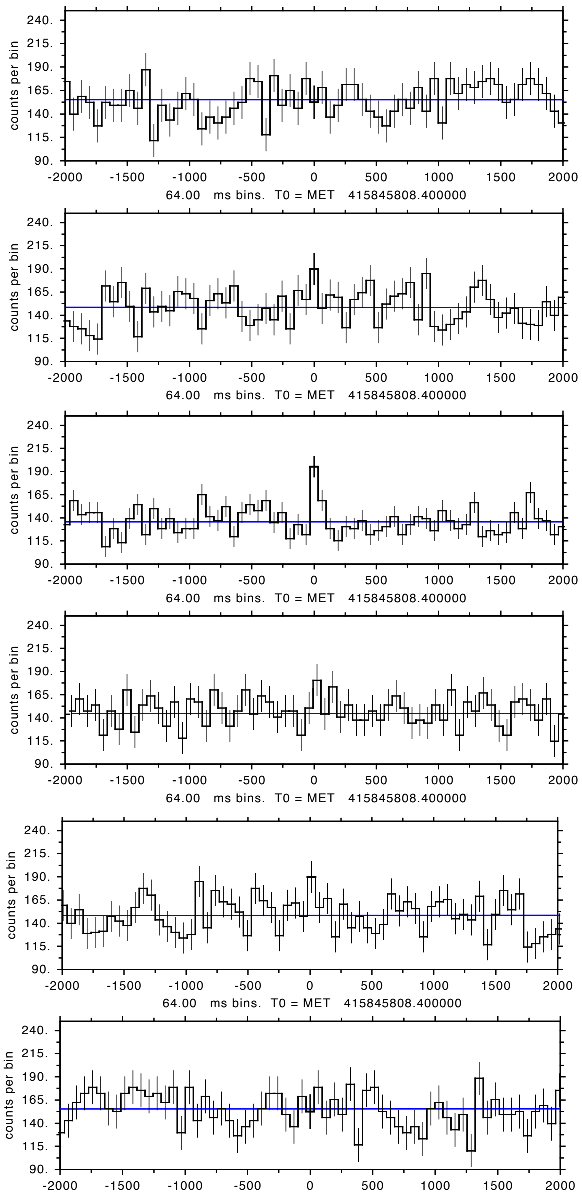
$$P(d_i|H_1) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_{d_i}} \exp\left(-\frac{(\tilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right)$$

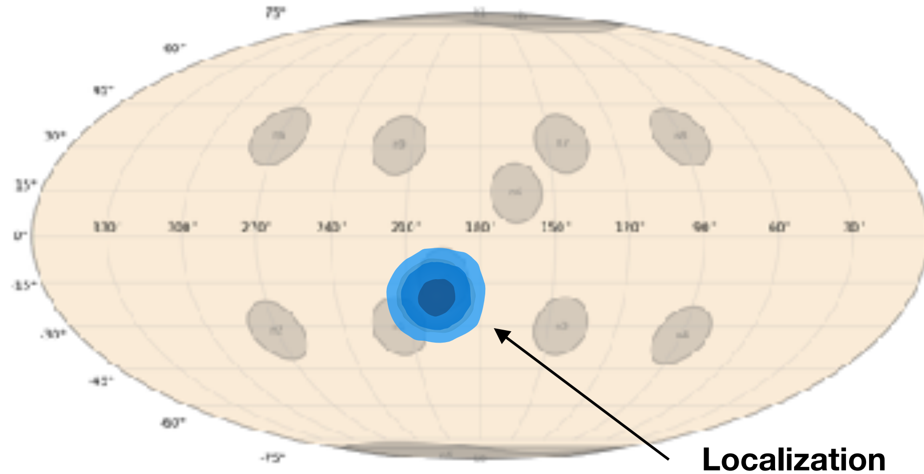
likelihood including signal model

$$P(d_i|H_0) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_{n_i}} \exp\left(-\frac{\tilde{d}_i^{\,2}}{2\sigma_{n_i}^2}\right)$$

likelihood from noise only

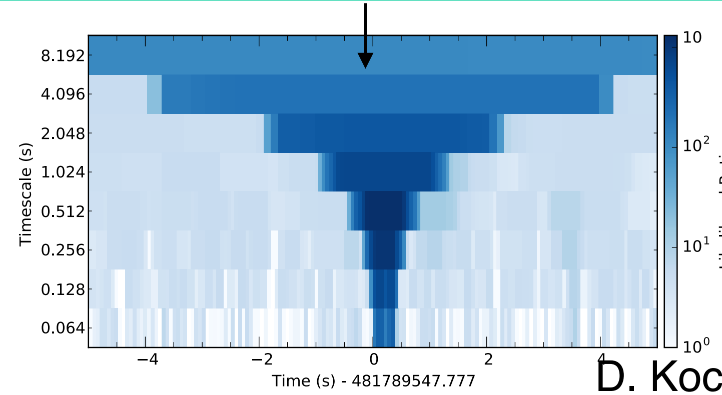
GBM Instrument Response





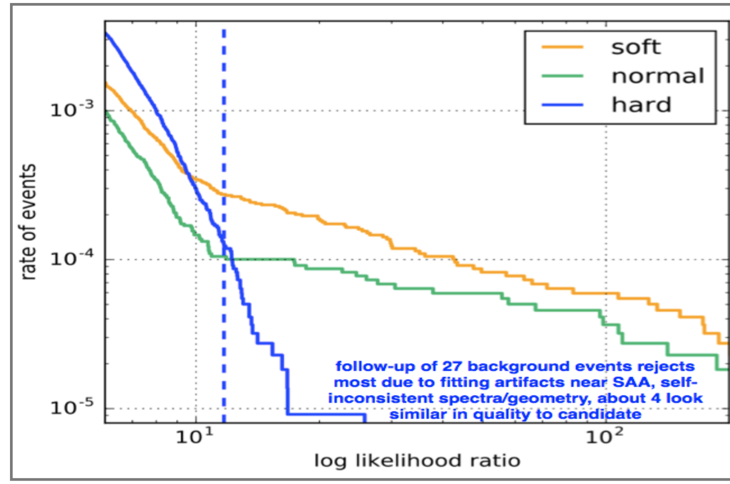
$$P(d_i|H_1) = \prod_i \frac{1}{\sqrt{2\pi\sigma_{d_i}}} \exp\left(-\frac{(\widetilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right)$$

$$\mathcal{L} = \sum_i \left[\ln\frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\widetilde{d}_i}{2\sigma_{n_i}^2} - \frac{(\widetilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right]$$



D. Kocevski

False Alarm Probability Calculation



False Alarm Rate (FAR) = 27 hard events in 218821.1s of GBM live time, factor of 3 for spectra searched, 90% confidence.

P = 2 x (4.79e-4 Hz) x 0.4s x (1 + ln(30s / 0.256s)) = 0.0022

Offset in time in either direction.

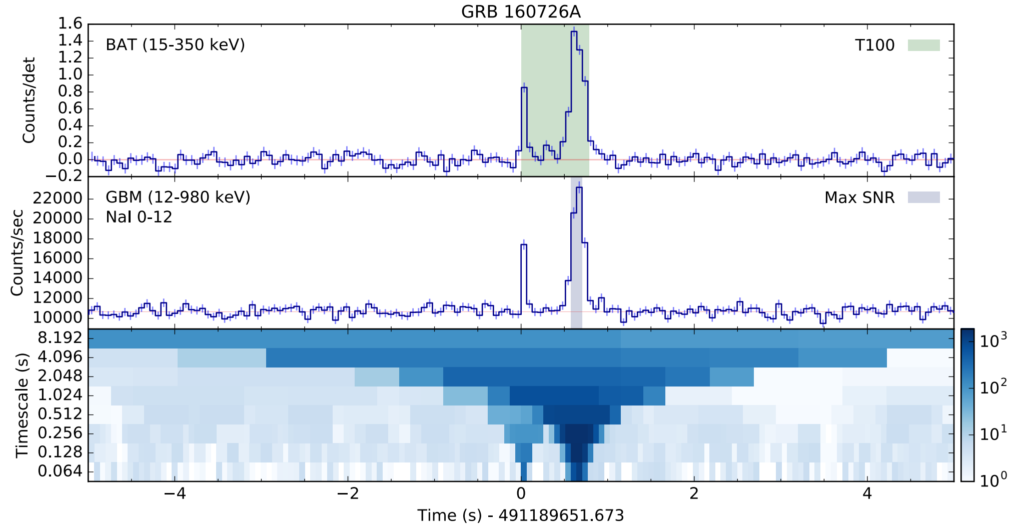
Time offset between GW and GBM event start.

Effective trials factor for bins/durations searched

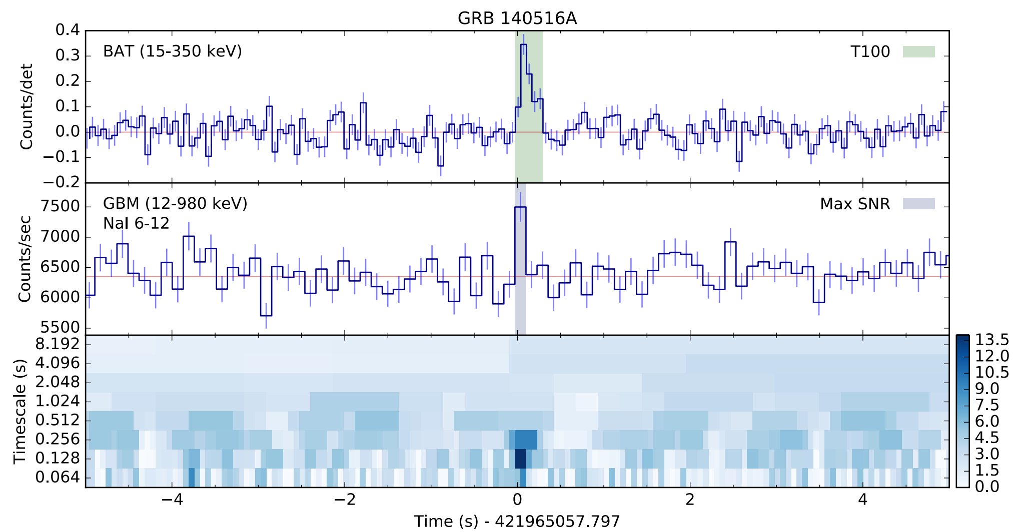
Control Sample: Swift Detected GRB

Kocevski et al., submitted

Swift GRB also triggered GBM



Swift GRB did not trigger GBM

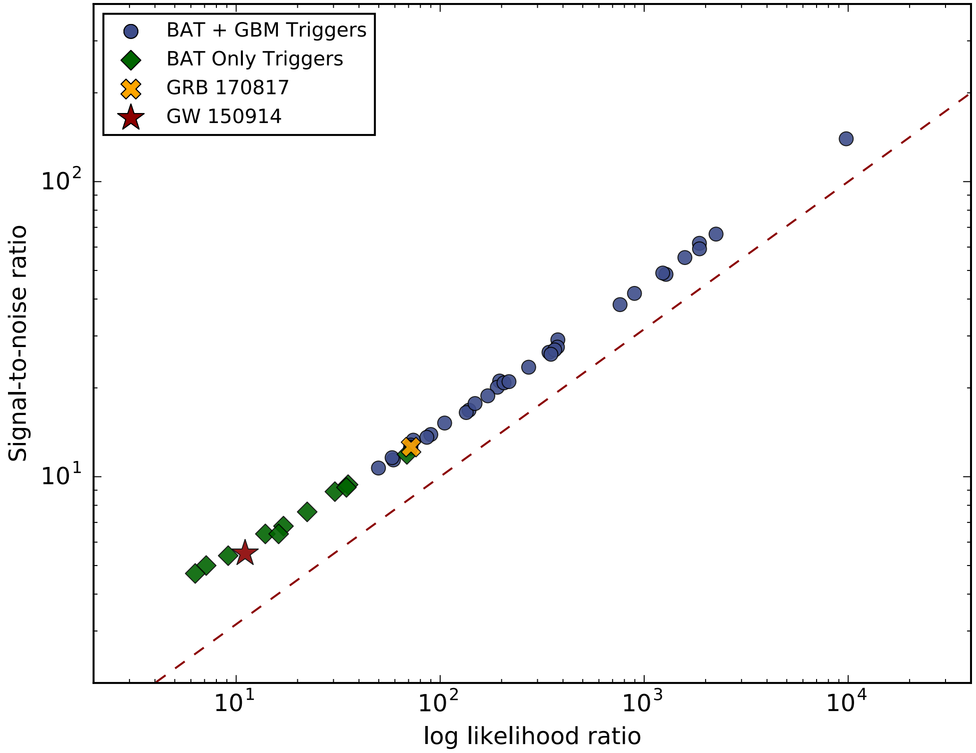


Control Sample: Swift Detected GRB

Kocevski et al., submitted

- 42 short GRBS detected by Swift BAT also in GBM FOV (2008 Aug 4 — 2017 Aug 4)
  - 31 detected by both instruments
  - 11 only by Swift
    - intrinsically dim and/or poor viewing geometry by GBM

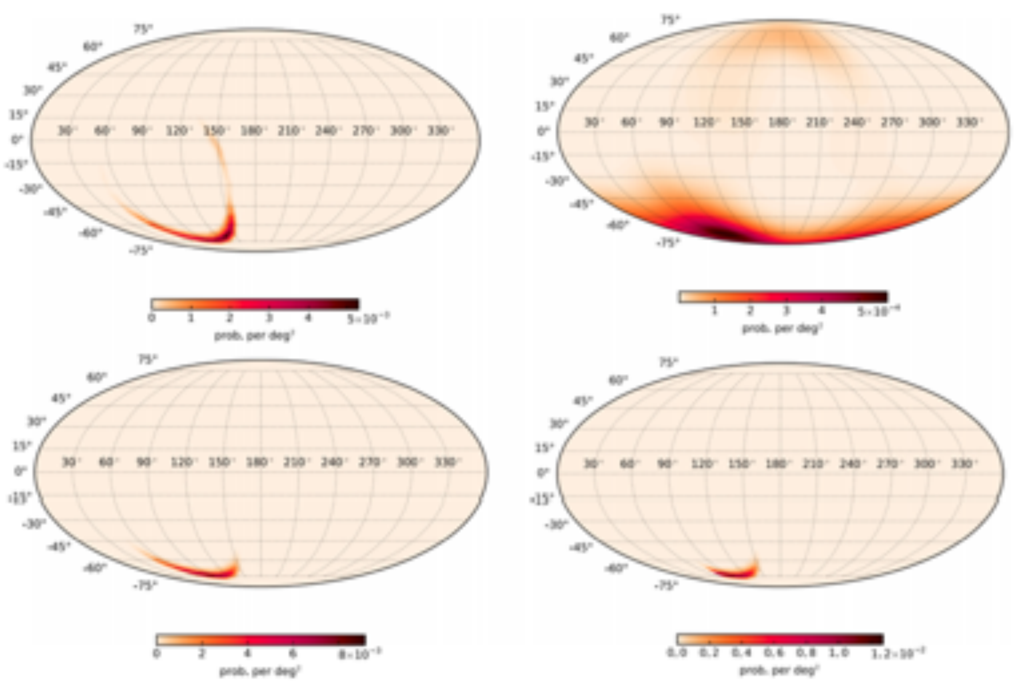
40/42 detected by the targeted search at >3σ (likelihood ratio >9)

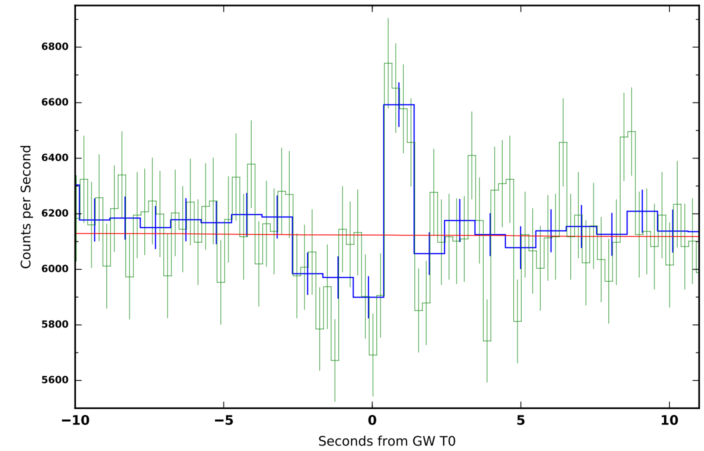


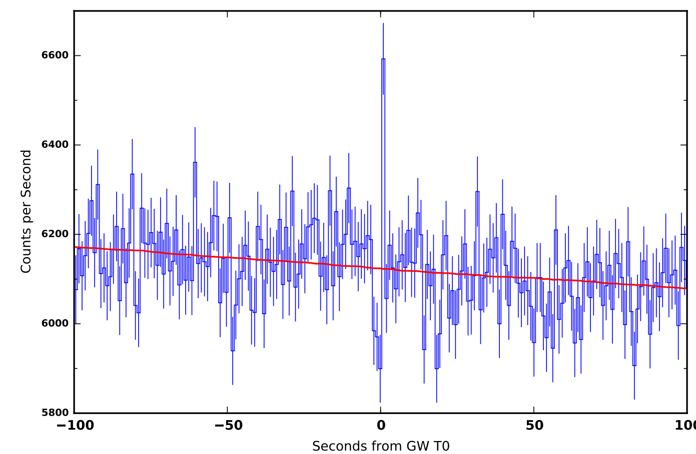
GRB 170817 can dim by 60% and still discoverable by this search
-> increases the volume of the Universe in which GRB 170817 could be detected by factor of 5

GW150914-GBM

- **Weak signal seen ~0.4 s after the GW trigger, ~1 s duration**
- **Did not trigger GBM onboard**
- **Targeted search: energy and detector coherent signal over all 14 detectors (Blackburn+ 2015)**
- **Raw summed light curve SNR ~6, >50 keV**
- **Large localization due to poor viewing geometry**



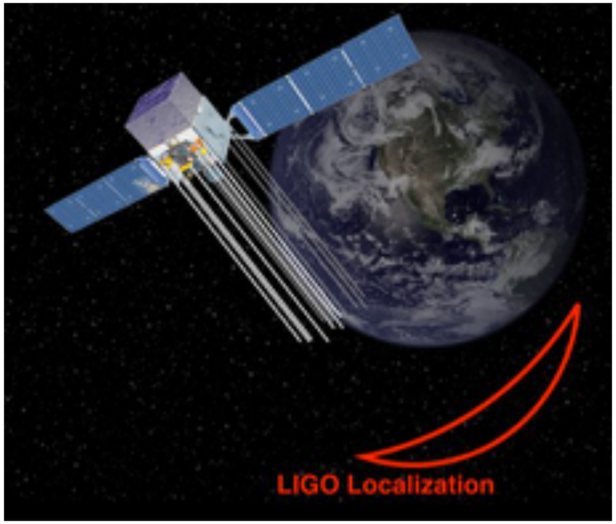




Connaughton et al. (2016)

GW150914-GBM

- No EM signal expected from BH-BH merger, resulting in much debate and theoretical speculation in the community
  - Rapidly rotating massive star causes dumbbell shaped core that collapses to BHs, merging together quickly with material around for GRB (Loeb et al. 2016)
  - Common envelope phase of merging close binaries (Woosley et al. 2016)
  - Extant BH-BH system that possesses a residual neutral disk at large radii suppressing the magneto-rotational instability (Perna et al. 2016)
  - Role of Winds (Murase et al. 2016)



- Greiner et al. 2016 claimed the signal was consistent with background
  - Only used 1 NaI and 1 BGO detector
  - Signal is only significant when adding all 14 detectors (poor geometry to GBM)
- Connaughton et al. 2018 rebuttal paper

What could the GBM event be?

GW150914

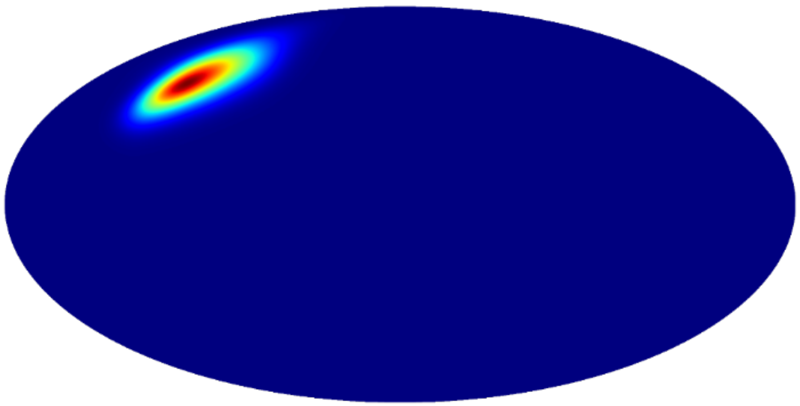
	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	**No**	**No**	**?**	**No**	**No**	**No**
Galactic Sources	**?**	**No**	**No**	**?**	**N/A**	**No**
Solar Activity	**?**	**No**	**No**	**No**	**N/A**	**No**
Magneto-spheric	**No**	**?**	**?**	**No**	**No**	**No**
Something New	**?**	**?**	**?**	**?**	**?**	**Maybe? Unlikely.**
Short GRB	**Yes**	**Yes**	**Yes**	**Yes**	**N/A**	**Yes**

Short GRB is the most likely explanation.

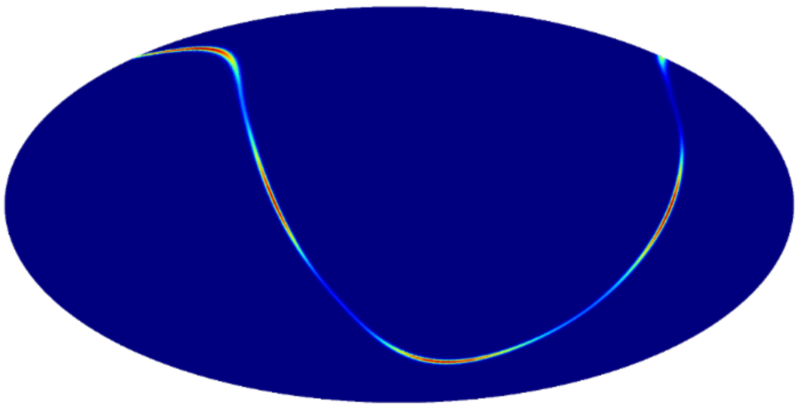
Joint LIGO-GBM Localizations

- **The combination of GBM+LIGO can significantly decrease the area in which to search for GW counterparts**

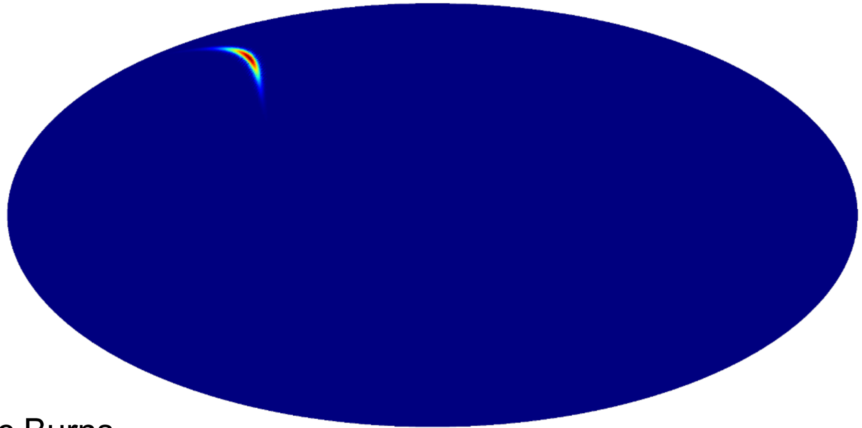
GBM



LIGO



GBM+LIGO



- **GBM ~ 10-100 deg^2**
- **LIGO ~ 100's deg^2**
- **GBM+LIGO ~ 10's deg^2**

Courtesy of Eric Burns

LAT as a GW Counterpart Detector

- LAT detects ~20 GRBs per year (1-2 short GRBs)
  - typically seeded by GBM & Swift GRB detections
  - LAT GRBs tend to be most energetic GRBs with bright afterglows
- LAT sees both prompt emission and afterglow emission
  - longest afterglow detected (GRB 130427A) lasted ~20 hours (Ackermann et al. 2014)
- LAT sees the entire sky every 3 hours
- LAT is the only instrument capable of searching for GRB afterglows <u>all-sky</u> in reasonable timeframe (~hours), without changing observing strategy
- A LAT counterpart would provide:
  - Localizations to aid broadband follow-up
  - High-energy measurement/constrains on prompt and/or afterglow spectra, emission mechanisms
  - constraint or measurement of bulk Lorentz Factor
  - constrain Lorentz Invariance Violation

Fermi Gamma-ray Space Telescope

Fermi Transient Searches

Pipeline
Method
Timescale
Distribution
Status

LAT Transient Factor (LTF)
Likelihood Around GBM/BAT triggers
seconds to orbits
LAT Team - Results in GCNs
Triggered Operating + *Blind Search Coming Soon*

***Fermi* All-sky Variability Analysis (FAVA)**
Counts Map Aperture Photometry
3 day (coming soon), 1 week
ATels
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/

GBM Targeted Searches (GW, neutrino)
ground search around external triggers
ms - s
GCNs

LAT Burst Advocate Tool
Likelihood Around GBM/BAT triggers
100 s, 1000 s
LAT Team - Results in GCNs
Operating

LAT Catalogs
Likelihood, associations
3 month (0FGL), 1 year (1FGL), 2 years (2FGL), 4 years (3FGL)
http://fermi.gsfc.nasa.gov/ssc/data/access/
4FGL in progress

LAT Automated Science Processing (ASP) + Flare Advocates
Likelihood
6 & 24 hour
ATels, GCN notices (on AGN)
Operating

GBM Untargeted Search
ground search
ms - s
GCN Notices
http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices
Operating

Pipelines

Timescale

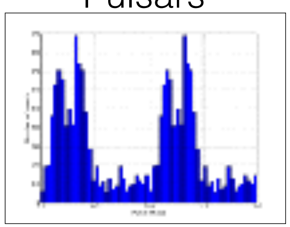
µs ***ms*** ***s*** ***minutes*** ***hours*** ***days*** ***months*** ***years***

Photon Timing

All Sky Cadence

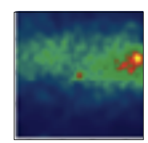
Transients

Pulsars



Solar Flares

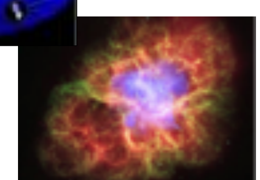
Novae



γ-ray Binaries

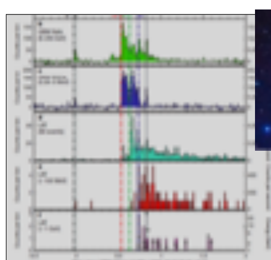
Blazar Flares

Crab Flares



Magnetar Flares

GRBs



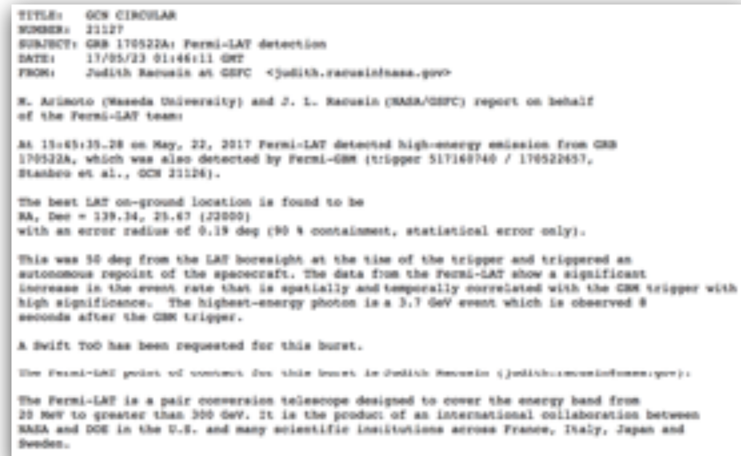
Terrestrial γ-ray Flashes

Not to scale

LAT Transient Factory (LTF) & Burst Advocate (BA) Tools

- Internal team pipelines that are seeded by GBM/Swift/INTEGRAL/etc.
- Search timescales from a few seconds to 10 ks
- Alerts LAT burst advocates of detections
- Used in preparation of GCN Circulars
- LTF Blind Search in the works

- Public products
  - GCN Circulars
  - GRB table: https://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/lat_grbs/table.php
- LTF developed by Giacomo Vianello & Nicola Omodei (Stanford)
- BA Tool developed by Dan Kocevski (NASA/MSFC)



```
TITLE:   GCN CIRCULAR
NUMBER:  21127
SUBJECT: GRB 170522A: Fermi-LAT detection
DATE:    17/05/23 01:46:11 GMT
FROM:    Judith Racusin at GSFC  <judith.racusin@nasa.gov>

M. Arimoto (Waseda University) and J. L. Racusin (NASA/GSFC) report on behalf
of the Fermi-LAT team:

At 15:45:35.28 on May, 22, 2017 Fermi-LAT detected high-energy emission from GRB
170522A, which was also detected by Fermi-GBM (trigger 517160740 / 170522657,
Stanbro et al., GCN 21126).

The best LAT on-ground location is found to be
RA, Dec = 139.34, 25.67 (J2000)
with an error radius of 0.19 deg (90 % containment, statistical error only).

This was 50 deg from the LAT boresight at the time of the trigger and triggered an
autonomous repoint of the spacecraft. The data from the Fermi-LAT show a significant
increase in the event rate that is spatially and temporally correlated with the GBM trigger with
high significance.  The highest-energy photon is a 3.7 GeV event which is observed 8
seconds after the GBM trigger.

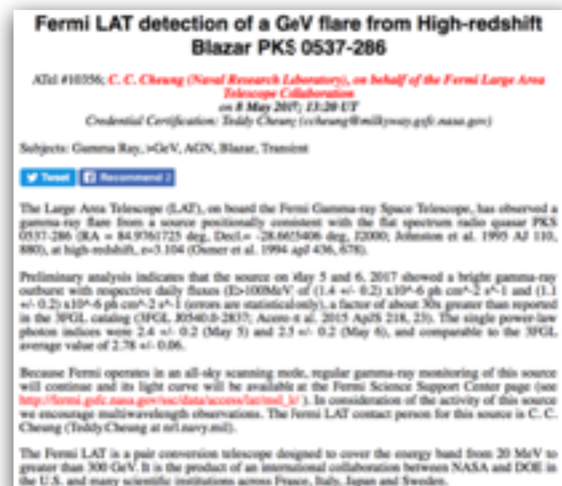
A Swift ToO has been requested for this burst.

The Fermi-LAT point of contact for this burst is Judith Racusin (judith.racusin@nasa.gov).

The Fermi-LAT is a pair conversion telescope designed to cover the energy band from
20 MeV to greater than 300 GeV. It is the product of an international collaboration between
NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and
Sweden.
```

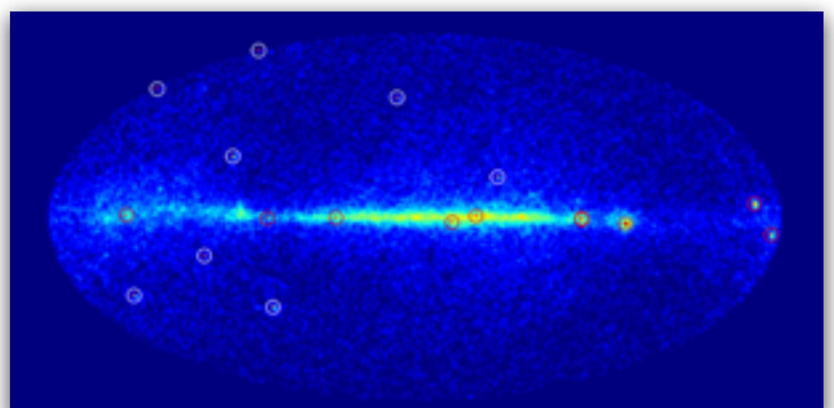
LAT Automated Science Pipeline (ASP)

- Search for flares in known sources (blazars, Galactic transients)
- Blind search transient sources on 6 hour & 24 hour timescales
- Used by the Flare Advocates to put out GCNs & ATels & to trigger follow-up observations with Swift, radio, optical
- Reports weekly on flaring sources: http://fermisky.blogspot.com/
- Nice description:
Ciprini et al. 2011, arXiv:1111.6803
- Developed by Jim Chiang, maintained by the flare advocates



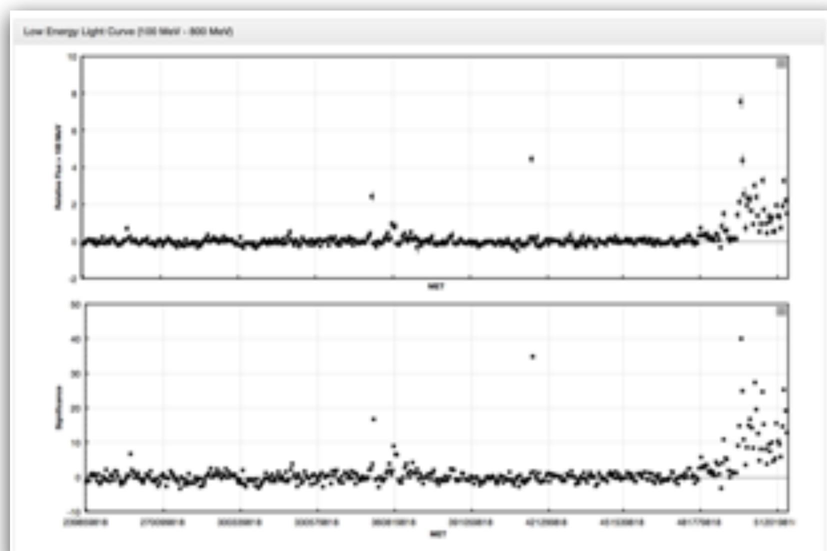
Fermi LAT detection of a GeV flare from High-redshift Blazar PKS 0537-286

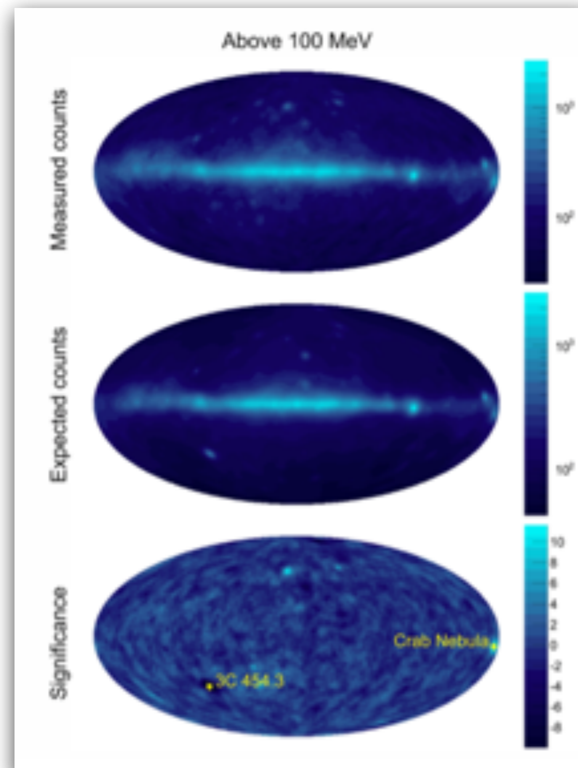
Subjects: Gamma Ray, >GeV, AGN, Blazar, Transient



Fermi All-Sky Variability Analysis (FAVA)

- Photometric technique for searching for flaring and variable sources relative to their average flux history
- Splits sky into thousands of pixels, and measures weekly time history of every pixel
- Pixels that flare above a 3σ significance threshold are followed-up by a standard likelihood analysis
- FAVA products public: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/index.php
- FAVA developed and operated by: Rolf Buehler, Dan Kocevski, Matteo Giommi, and Marco Ajello

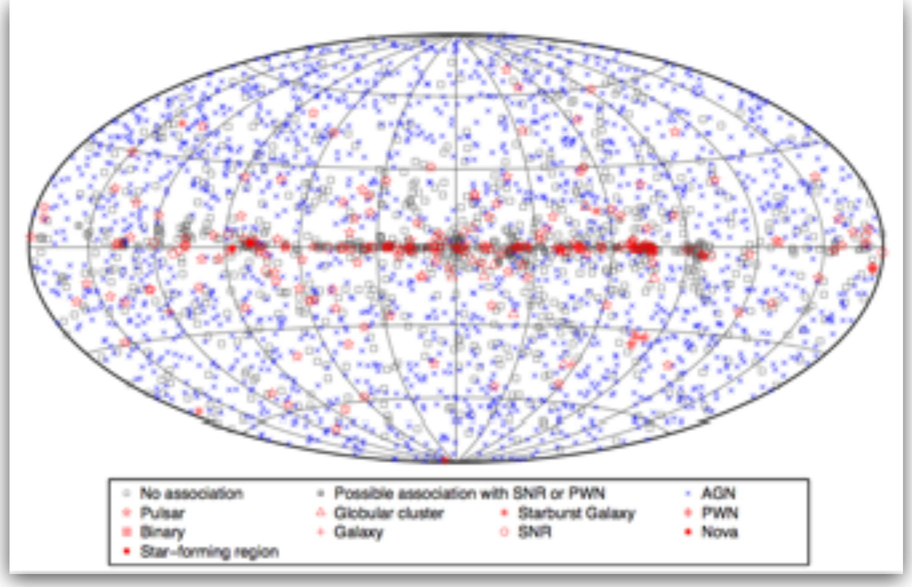




Ackermann et al. 2013

LAT Catalogs

- General Catalogs - 0FGL, 1FGL, 2FGL, 3FGL
- High-Energy Catalogs - 1FHL, 2FHL
- Flaring Source Catalogs - 1FAV, 2FAV
- https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/
- Provides source descriptions for steady sources, or sources flaring enough to be significant in catalog interval
- Relevant for comparisons to sources detected during transient searches



http://www.asdc.asi.it/fermi3fgl/

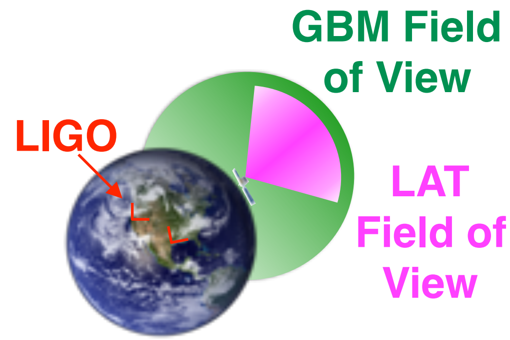
Custom LAT GW Counterpart Searches

- Large GW localization regions present unique challenges
  - GW Seed provides time, but large sky region
  - LAT has a large field of view, but exposure varies throughout 2 orbit rocking profile
- GeV band has low rate of transients on short timescales
- GBM provides all-sky coverage (not occulted by Earth), which could provide seed
- LAT team (Giacomo Vianello, Nicola Omodei, Dan Kocevski) have developed pipelines to split LIGO 90% localization contours into pixels (sized ~LAT PSF at 1 GeV) and performed likelihood analyses on each pixel searching for excesses
- Depends on time intervals chosen - requires balance between sky coverage and exposure at each point

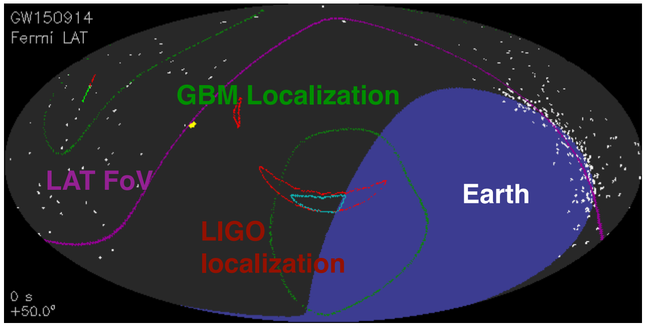
Fermi Observations of GW Detections and Candidates

- **Fermi Observations of LIGO detections and candidates**

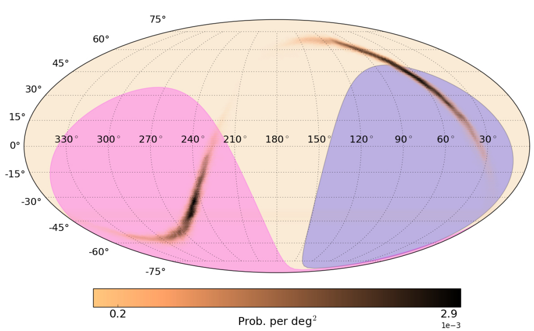
	GW150914	LVT151012	GW151226
GBM coverage of LIGO region at trigger time	75%	68%	83%
GBM observed entire LIGO region within	25 min	8 min	34 min
LAT coverage of LIGO region at trigger time	0%	47%	32%
LAT observed entire LIGO region within	70 min	113 min	140 min



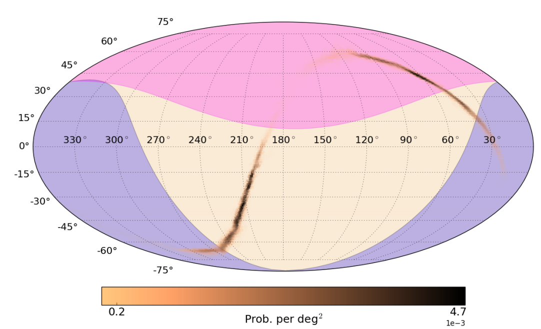
GW150914



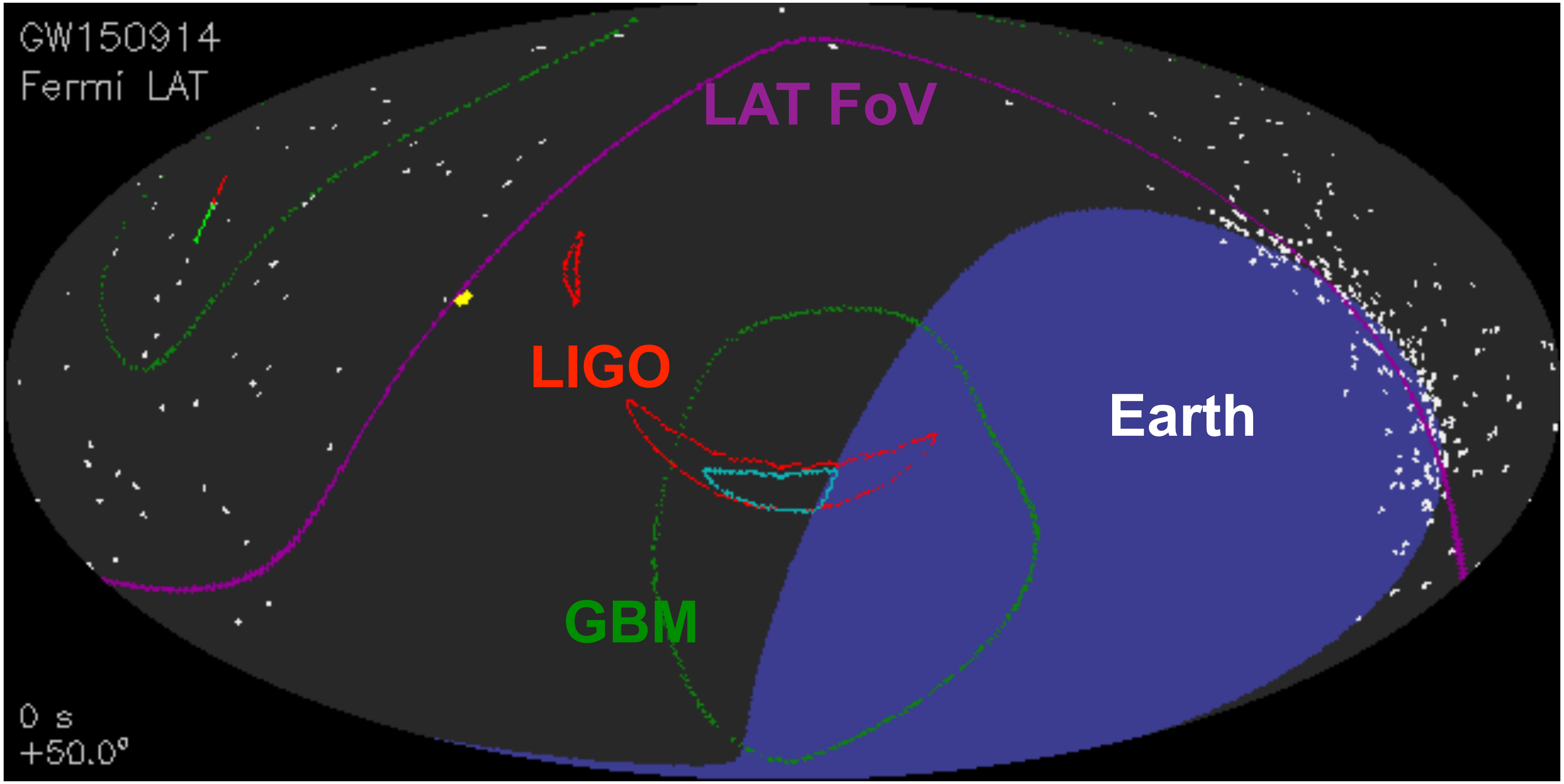
LVT151012



GW151226

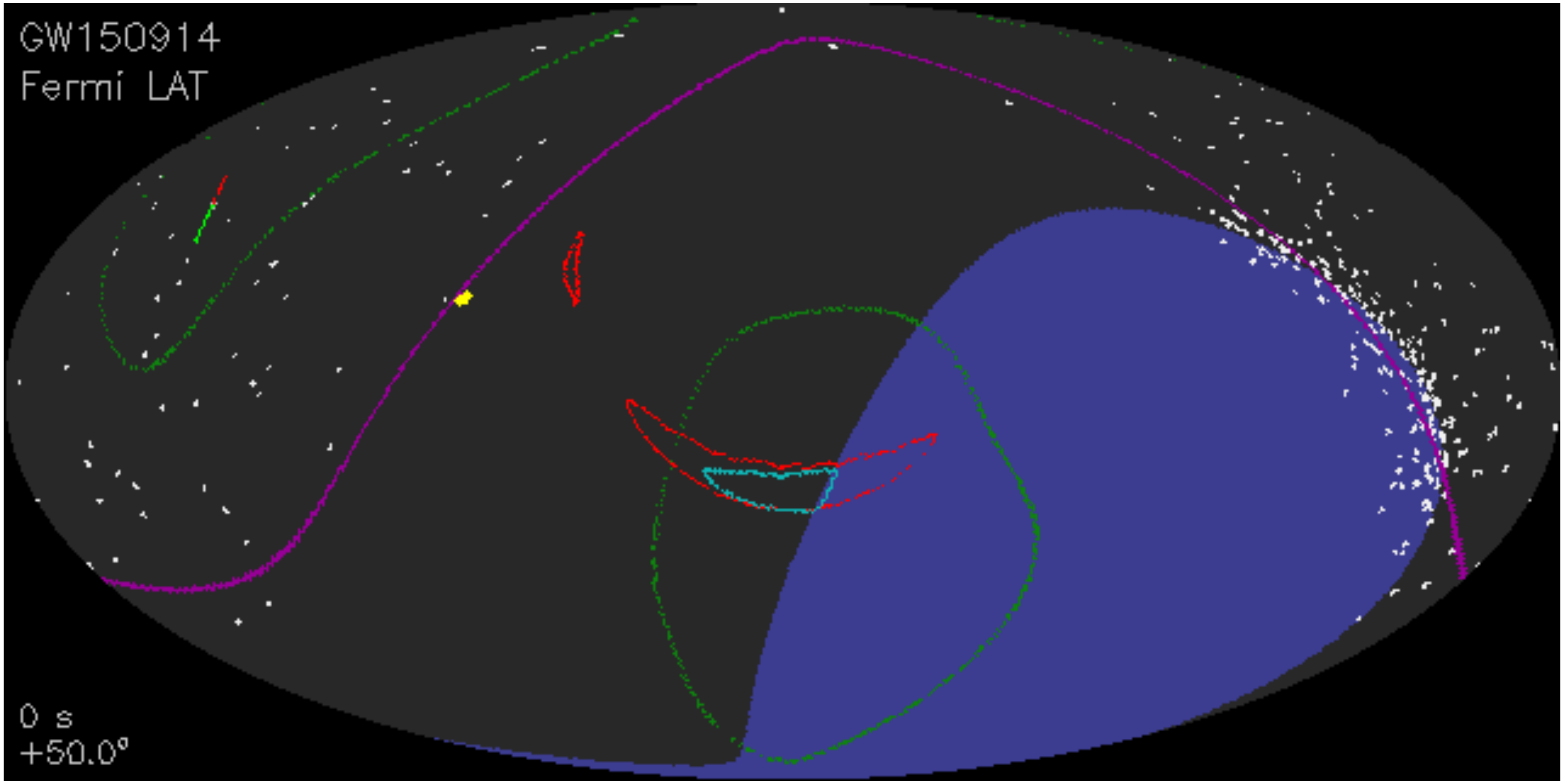


Fermi Coverage of GW150914



Credit: Seth Digel

Fermi Coverage of GW150914

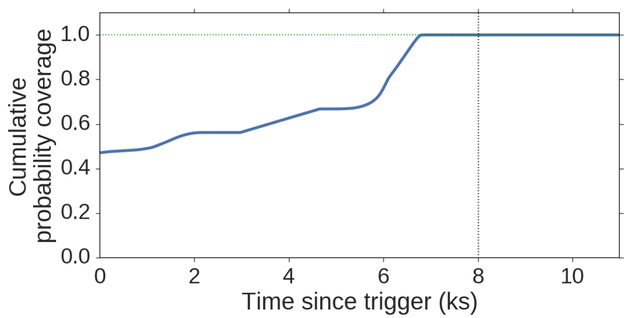


Credit: Seth Digel

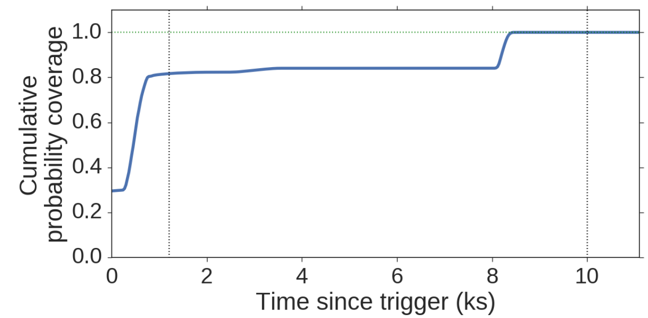
Fixed Time Window

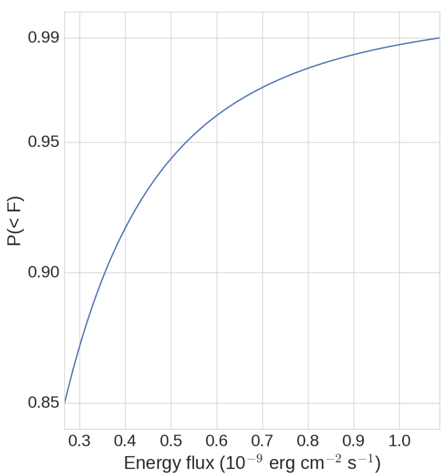
- Fixed interval (± 10 s, 0-10 ks), time it took for LAT to observe 90% of LIGO localization region
- Likelihood analysis performed on each sky pixel over that region
- Flux upper bounds measured for each pixel
- Useful to place single global upper bound in some interval

LVT151012



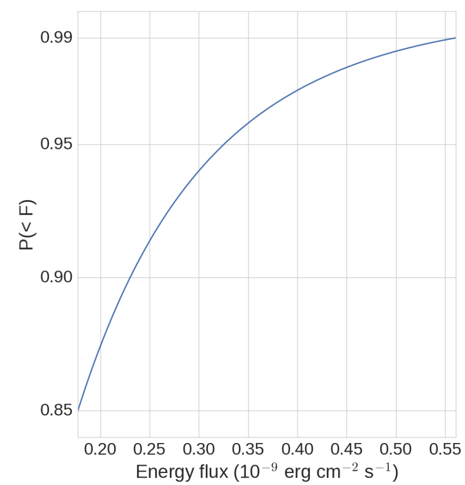
GW151226





Flux upper bound corresponding to credibility level

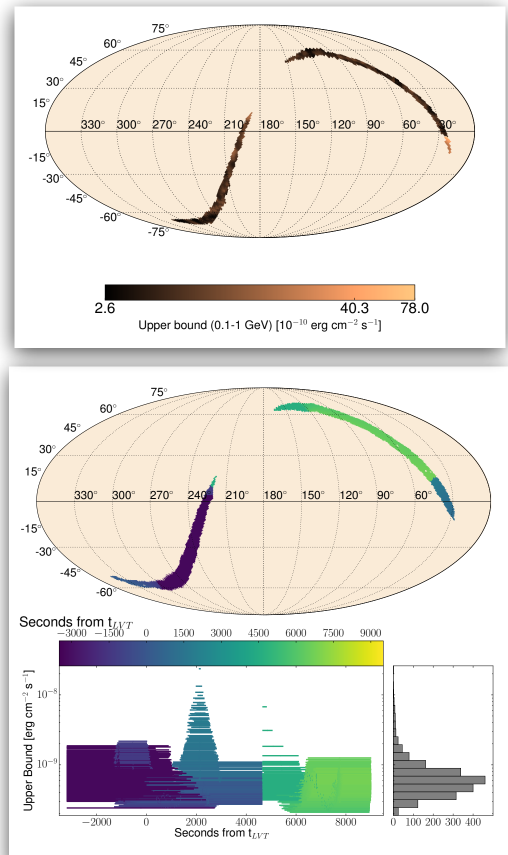
Racusin et al 2017, Vianello et al. 2017



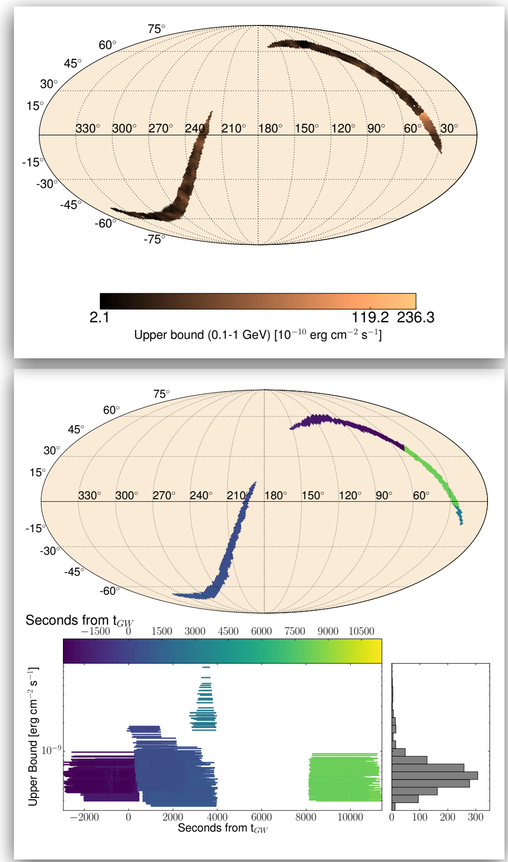
Adaptive Time Windows

- **Time interval set by period in which each pixel in GW localization passed through LAT FoV during some interval (e.g. first two orbits)**
- **Useful to evaluate LAT upper bound at specific location (e.g. like that of an external counterpart)**

LVT151012



GW151226



Racusin et al 2017, Vianello et al. 2017

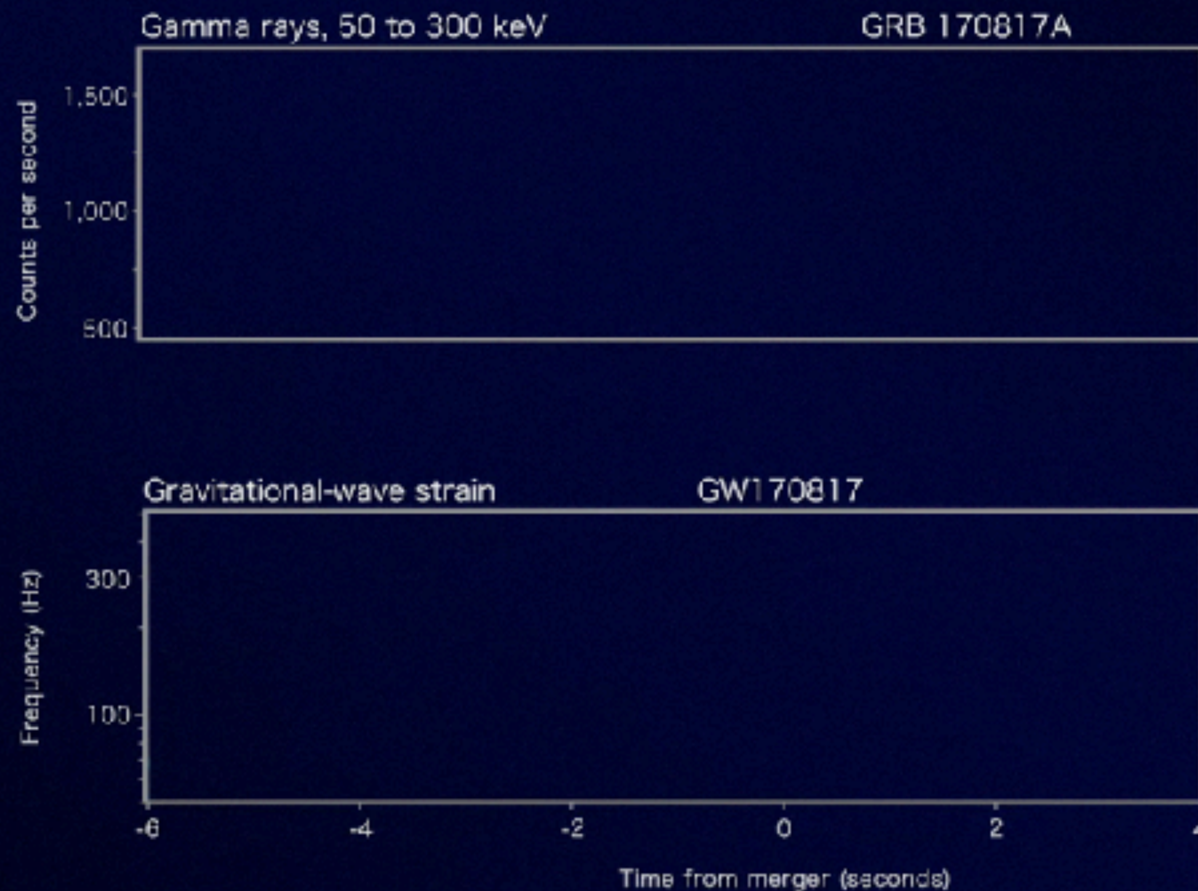
BH-BH Merger Results

- GW150914-GBM only candidate counterpart found by GBM, no counterpart seen for LVT151012, GW151226, GW170104, GW170608, GW170814
- No candidate counterparts found by LAT for GW merger events using any of the techniques described
- Lack of GBM counterpart for other events does not contradict GW150914-GBM
  - LIGO localization regions not fully covered at time of triggers
  - to-date GW150914 still has the highest mass and lowest distance, which might correspond to luminosity
  - GBM background rates higher at the times of LVT151012 & GW151226 that GW150914-GBM

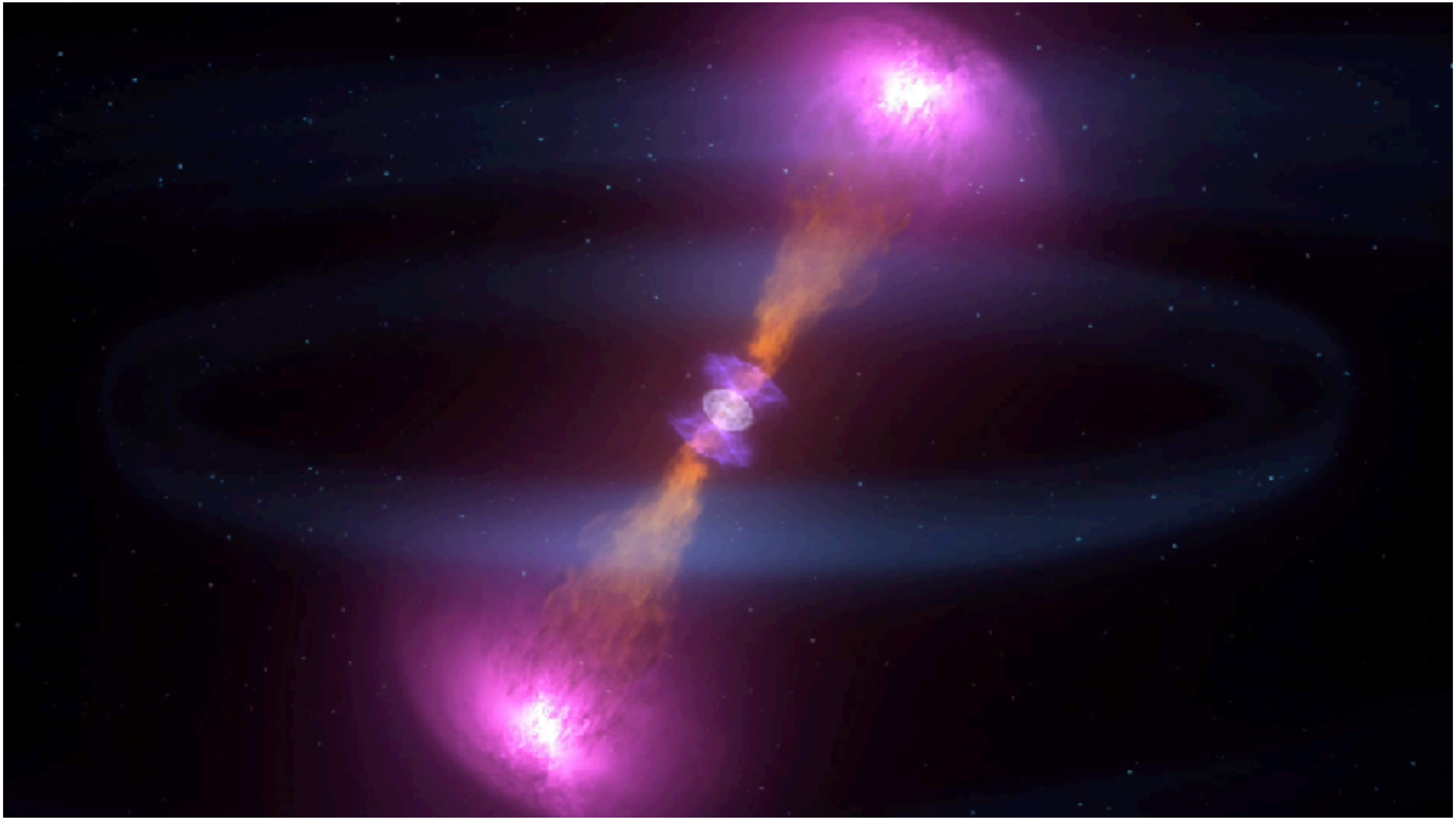
GW170817/GRB170817A

Fermi

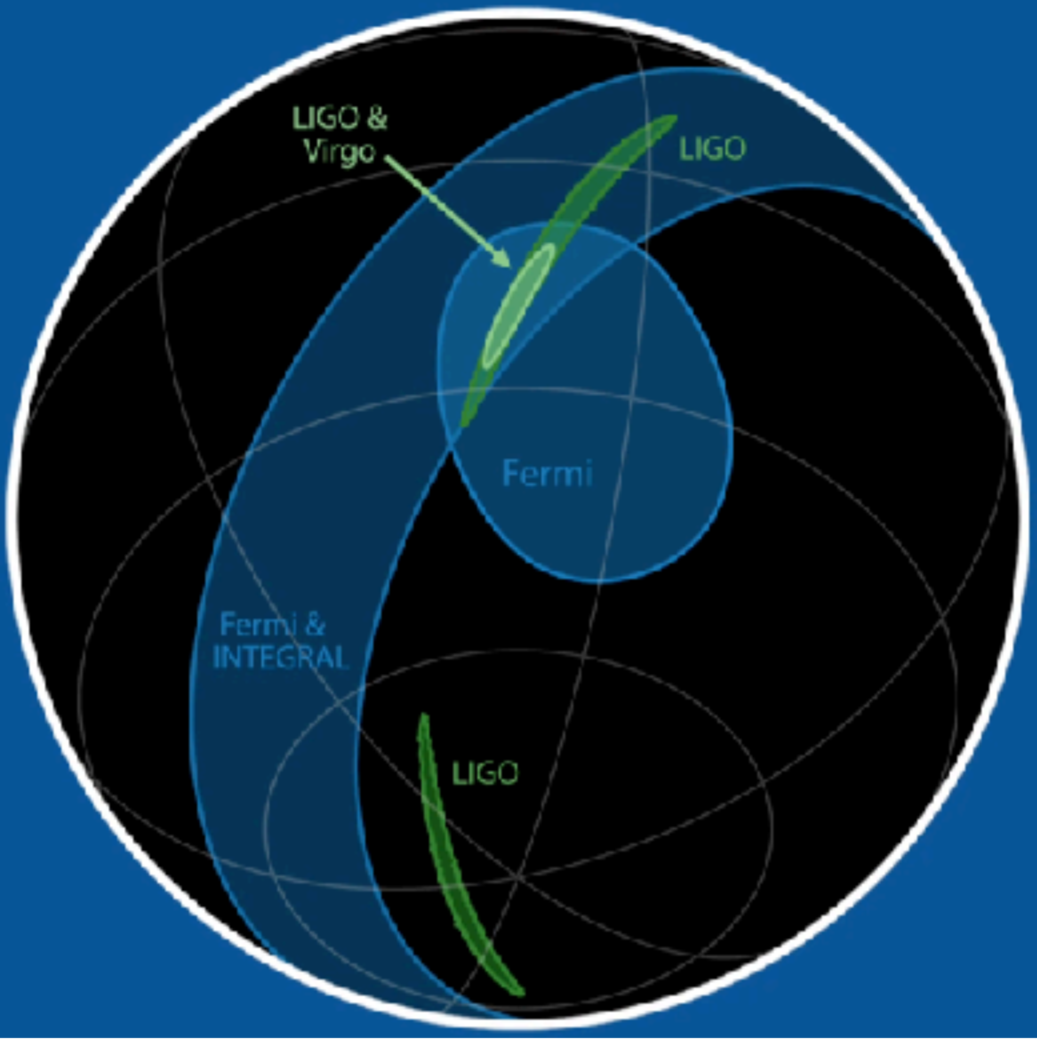
LIGO

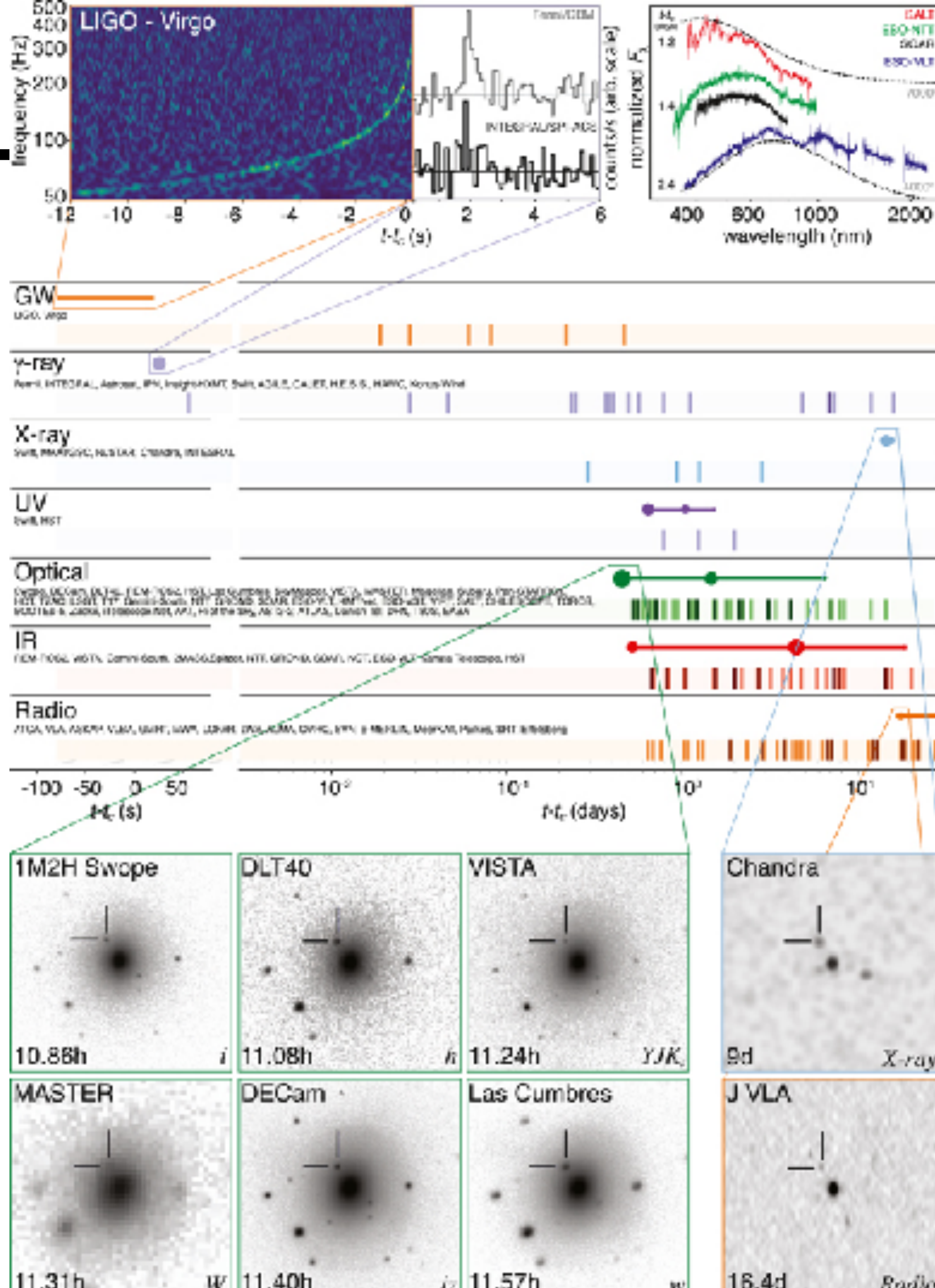


GW170817/GRB170817A



GW170817/GRB170817A



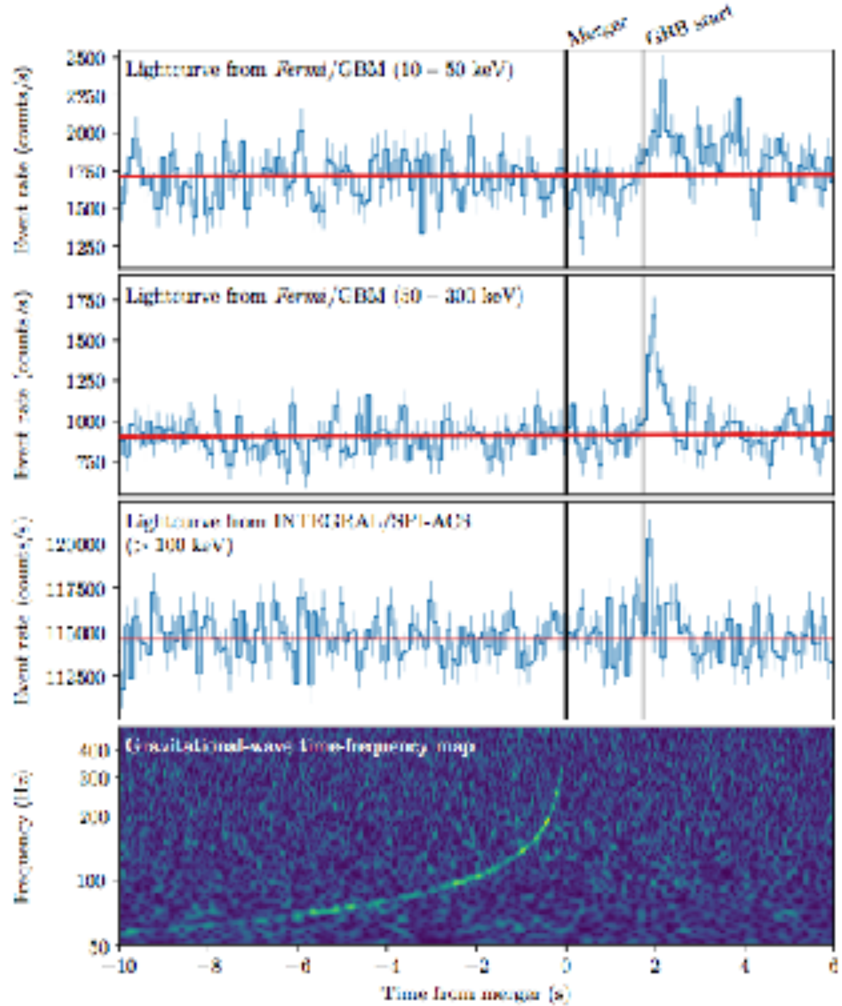


Abbott et al. 2017

The First Unambiguous Gravitational Wave Counterpart

- **GRB170817A / SSS17A / AT 2017gfo**
  - Short GRB 1.7 s after GW merger
  - D_{GW} = 40 +/- 8 Mpc
  - $D_{host\ galaxy}$ =42.9 Mpc
  - E_{iso} = 3×10^{46} erg

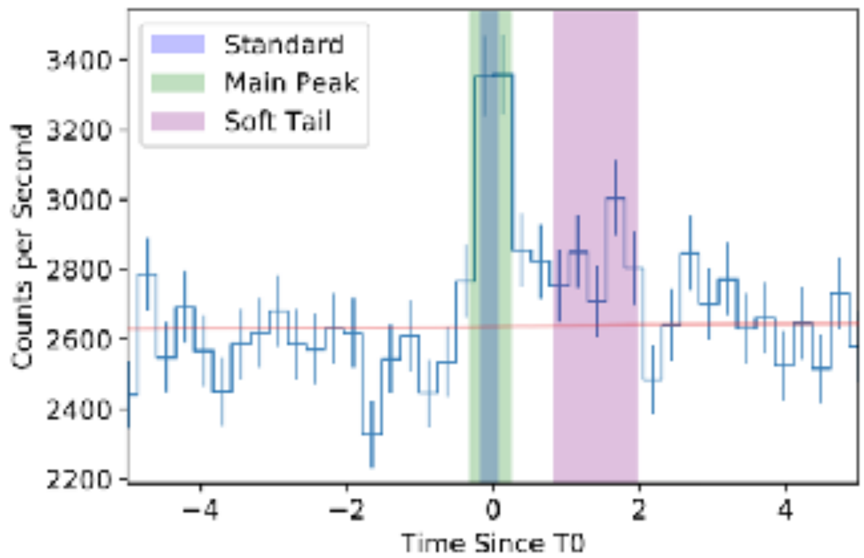
  - Optical counterpart detected at T_0+11 hours
  - Blue + red kilonova over days/ weeks afterwards
  - Apparent off-axis late-peaking X-ray/radio/optical afterglow

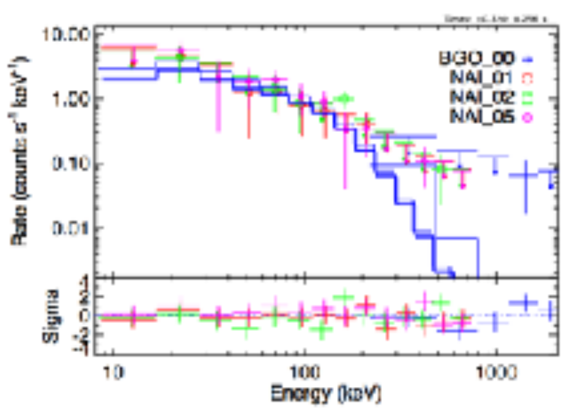


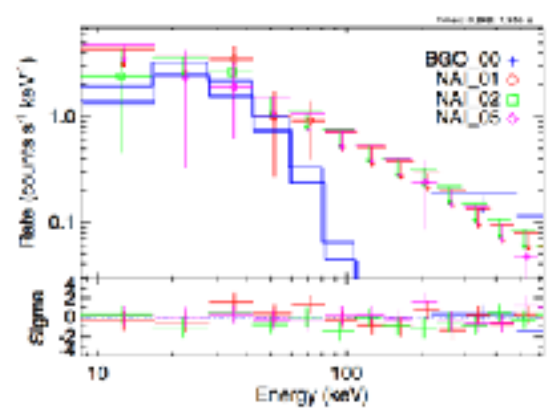
Abbott et al. 2017, ApJL

GRB 170817A Spectral Components

- **Typical short (~0.5 s) hard spike**
  - $\alpha = -0.62 \pm 0.40$
  - $E_{peak} = 185 \pm 62$ keV
- **Longer (~1 s) soft thermal tail**
  - $kT = 10.3 \pm 1.5$ keV

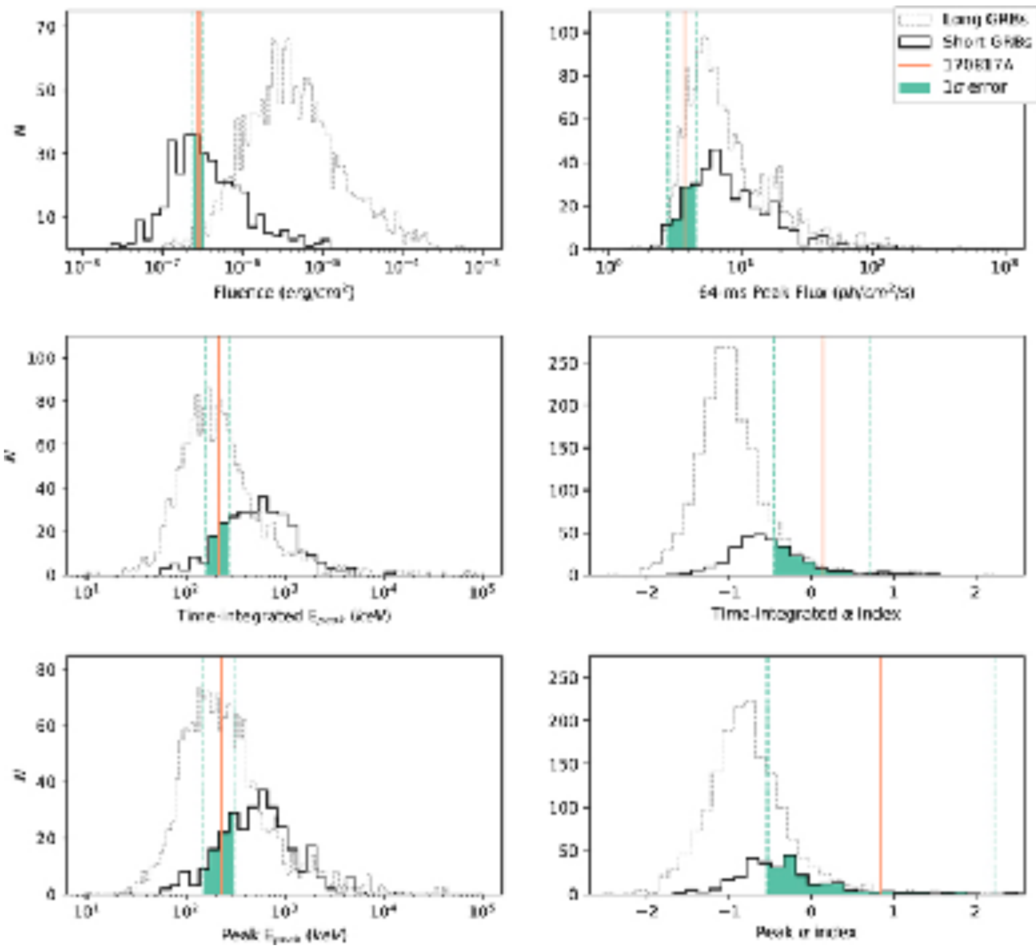


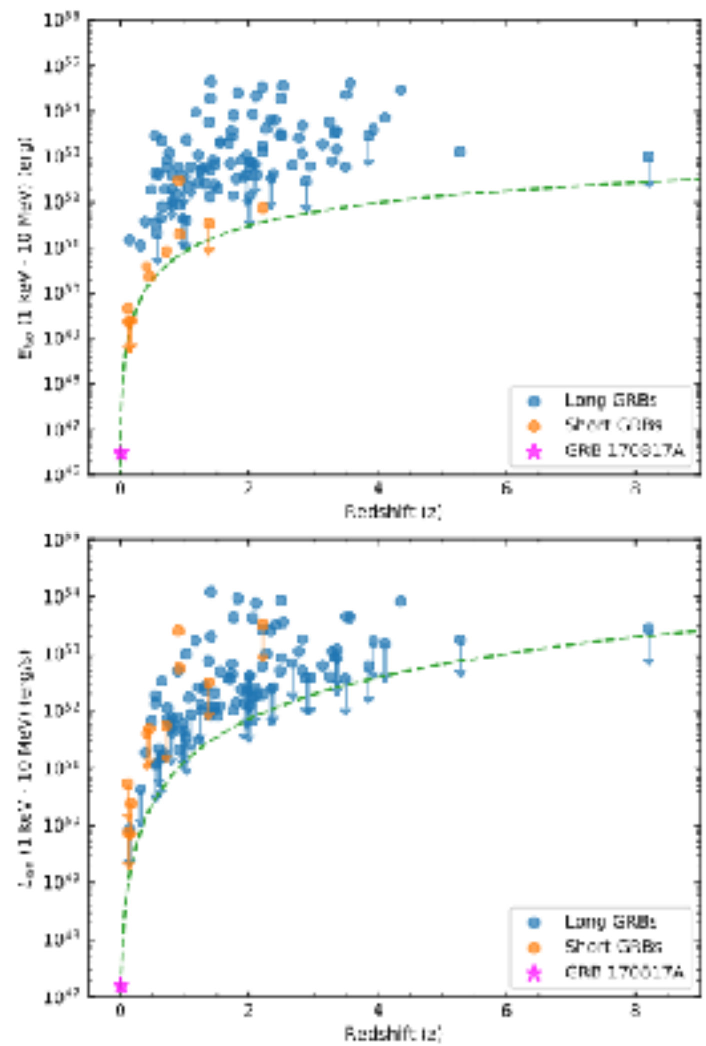




Goldstein et al. 2017

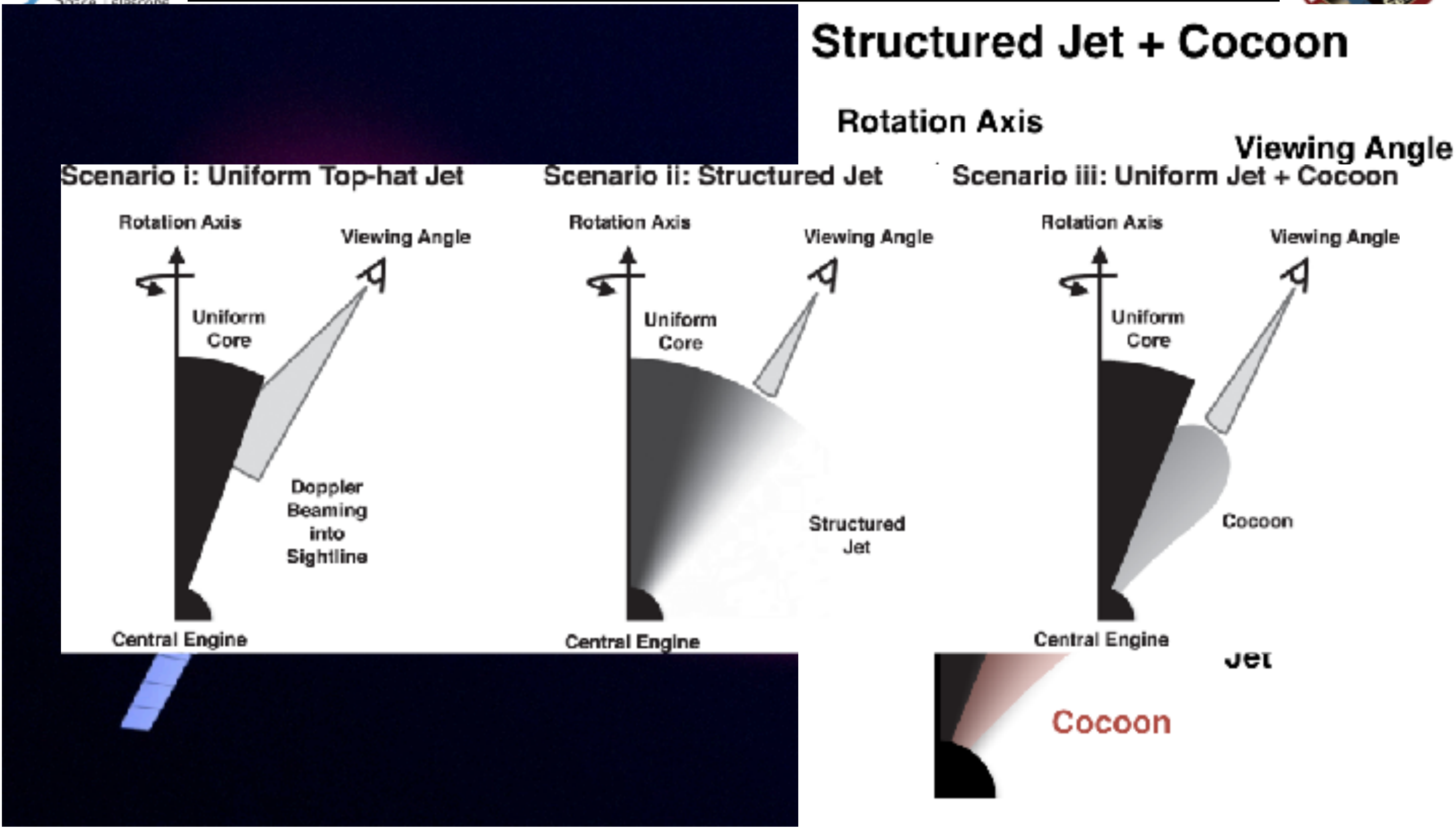
GRB 170817A Properties





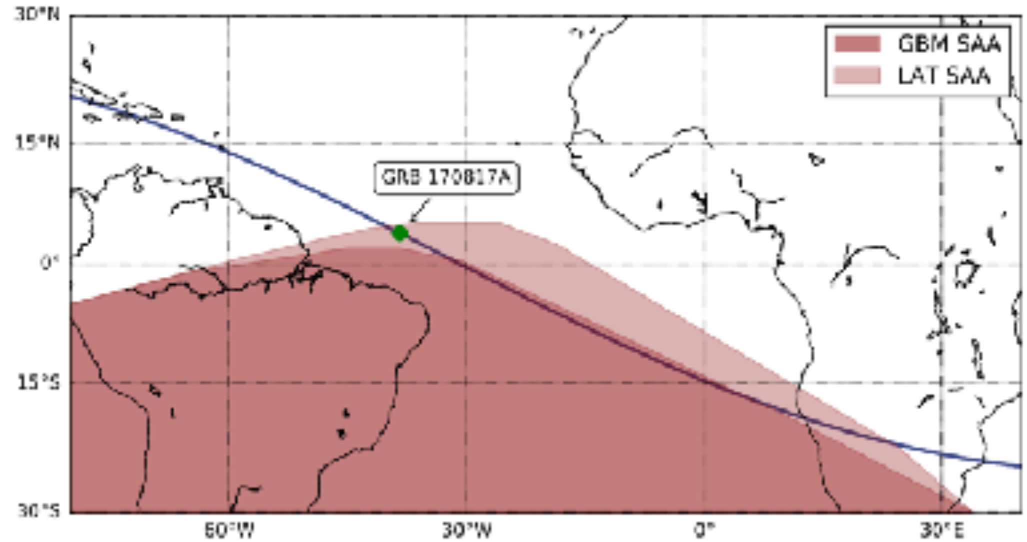
Goldstein et al. 2017 **Abbott et al. 2017**

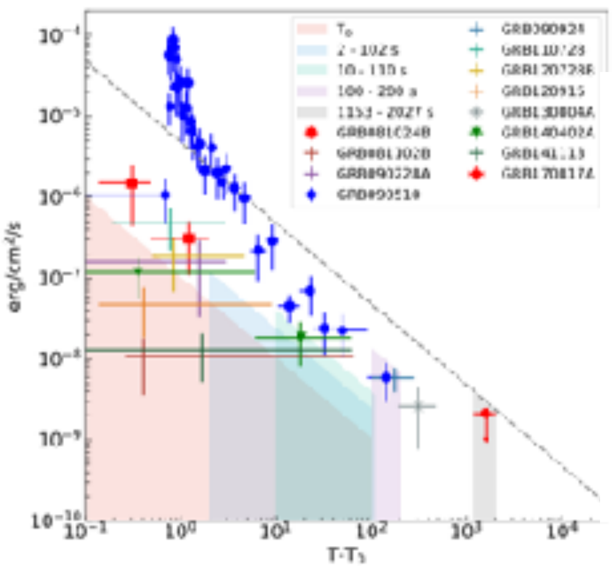
Jet/Cocoon Structure

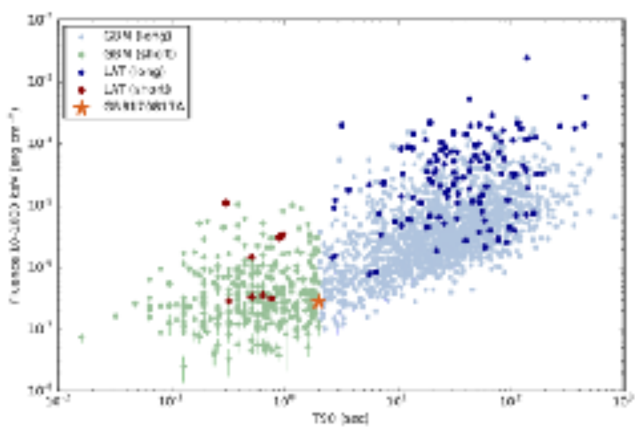


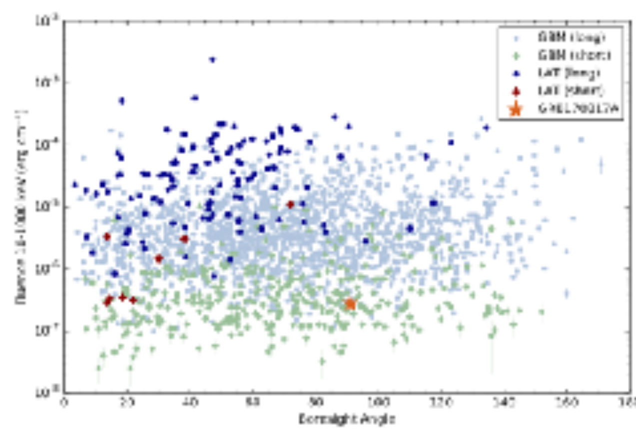
Fermi-LAT Observations of GW170817/GRB170817A

- **LAT was not taking data at merger time (SAA)**
- **Upper limit from first observation perhaps in realm of detections of other LAT short GRBs**



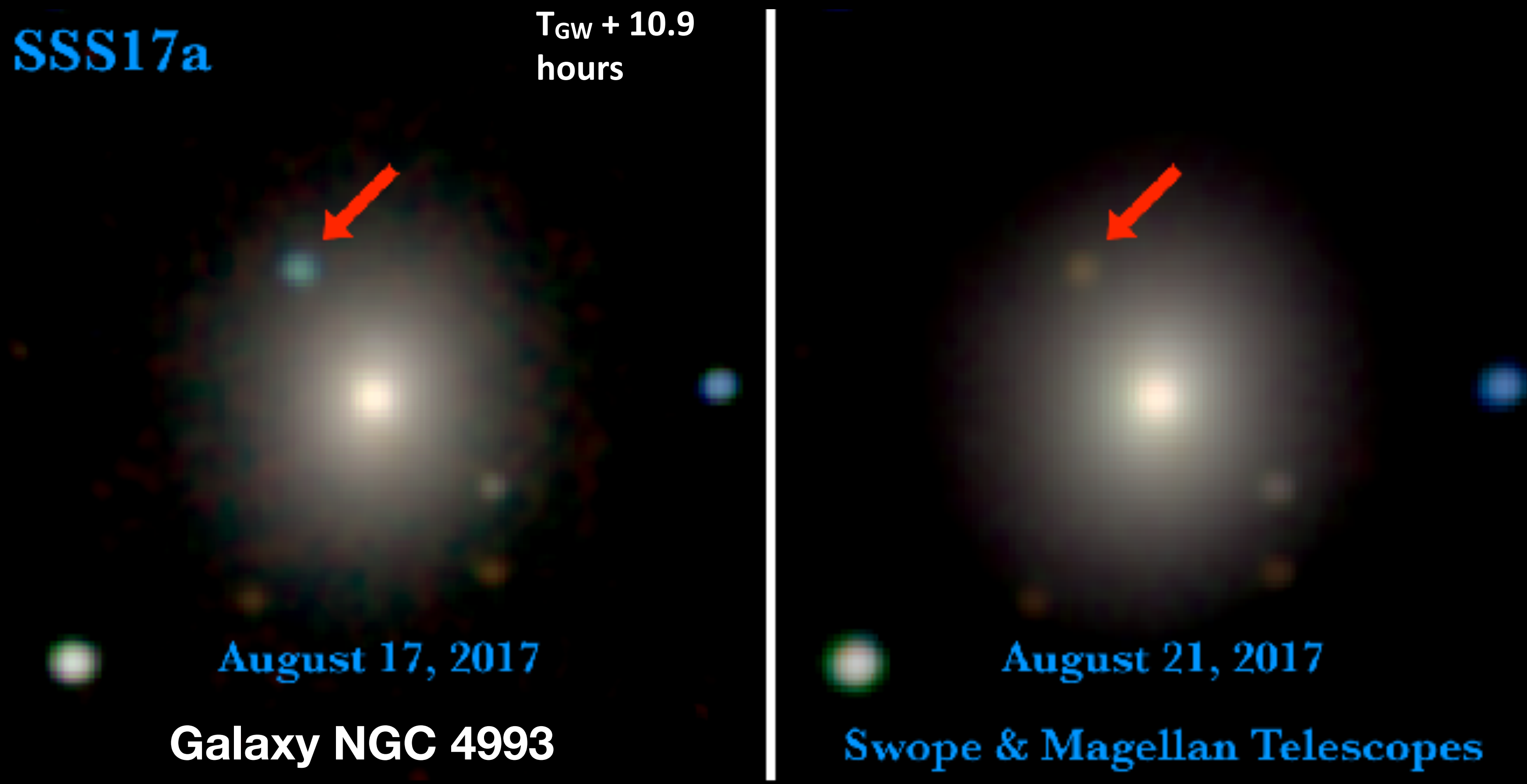






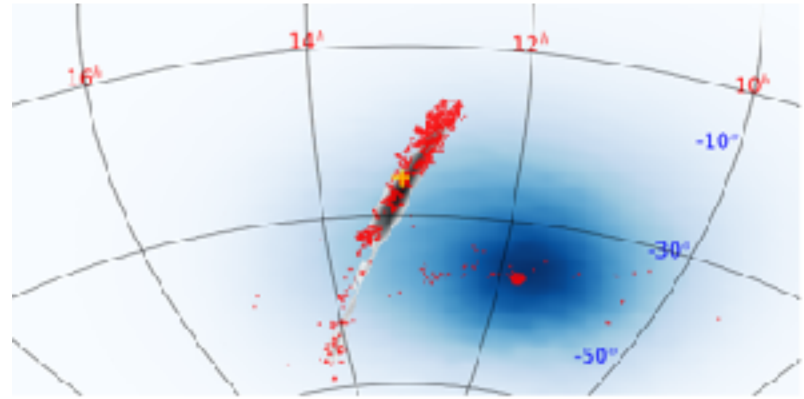
LAT Collaboration et al., 2017, arXiV:1710.05450

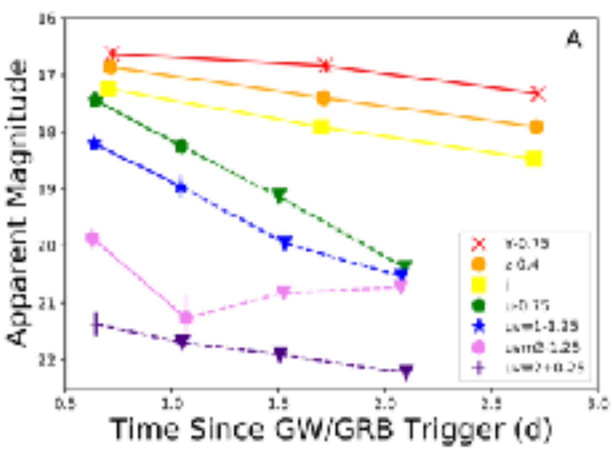
Optical Counterpart & Host Galaxy

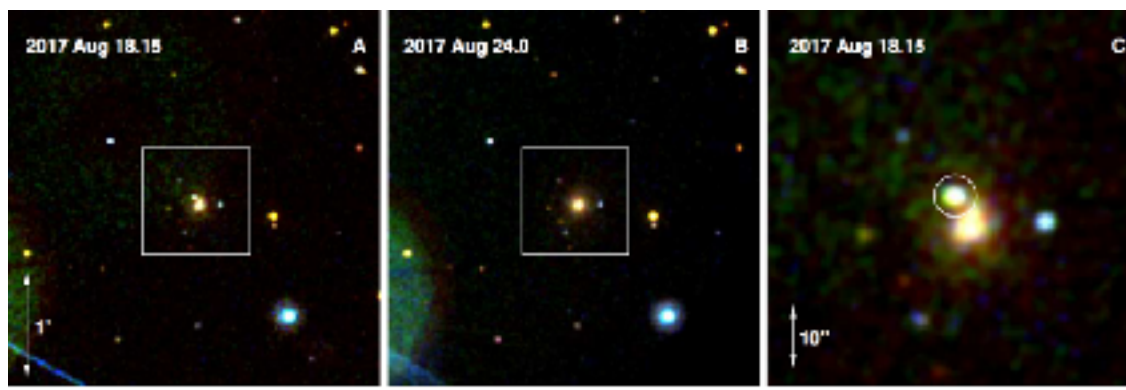


Swift Observations

- See Evans et al. 2017 for more details
- GW170817 occulted by Earth for Swift at time of merger (no BAT observations)
- XRT/UVOT began follow-up observations of GBM localization within ~1 hour
- UVOT detected bright UV counterpart at ~0.6 days at location of Swopes optical counterpart

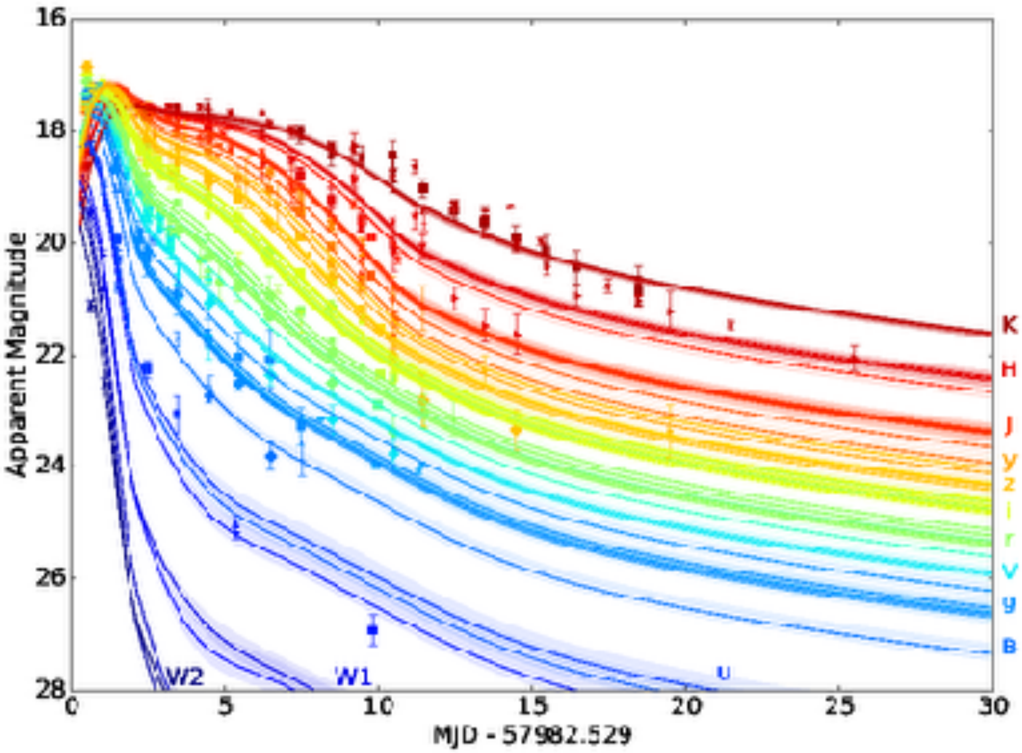




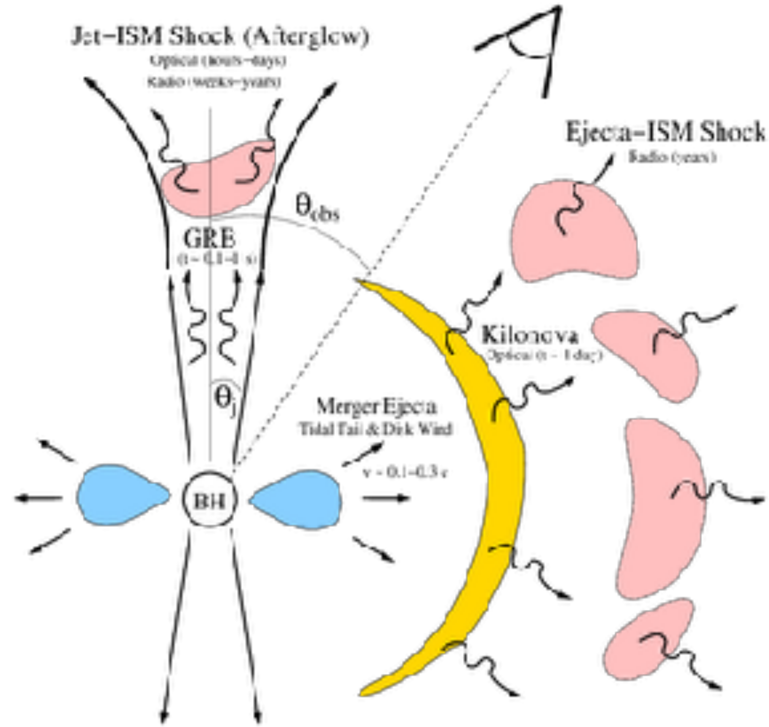


Evans et al. 2017, Science

Kilonova

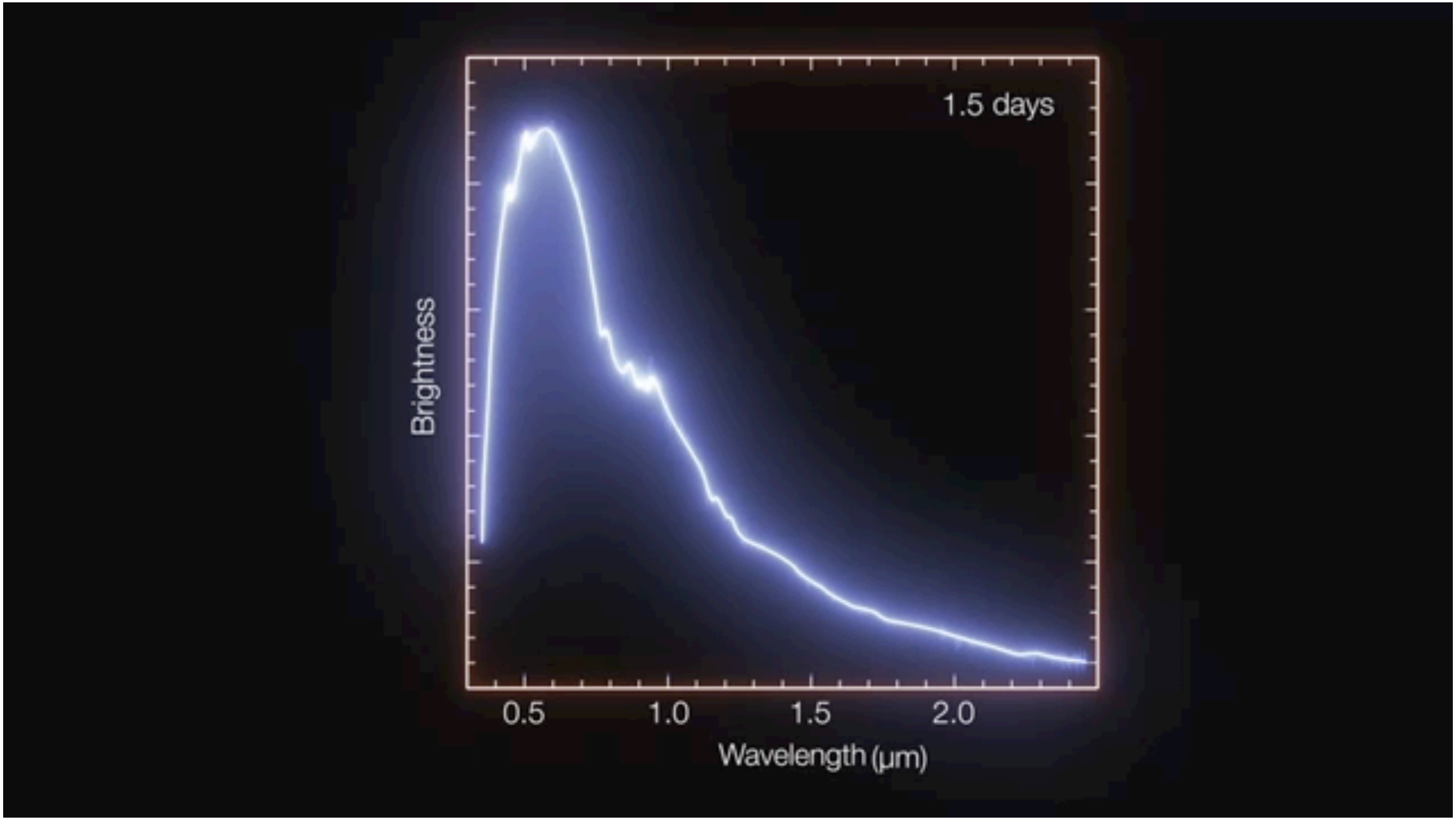


Villar et al. 2017

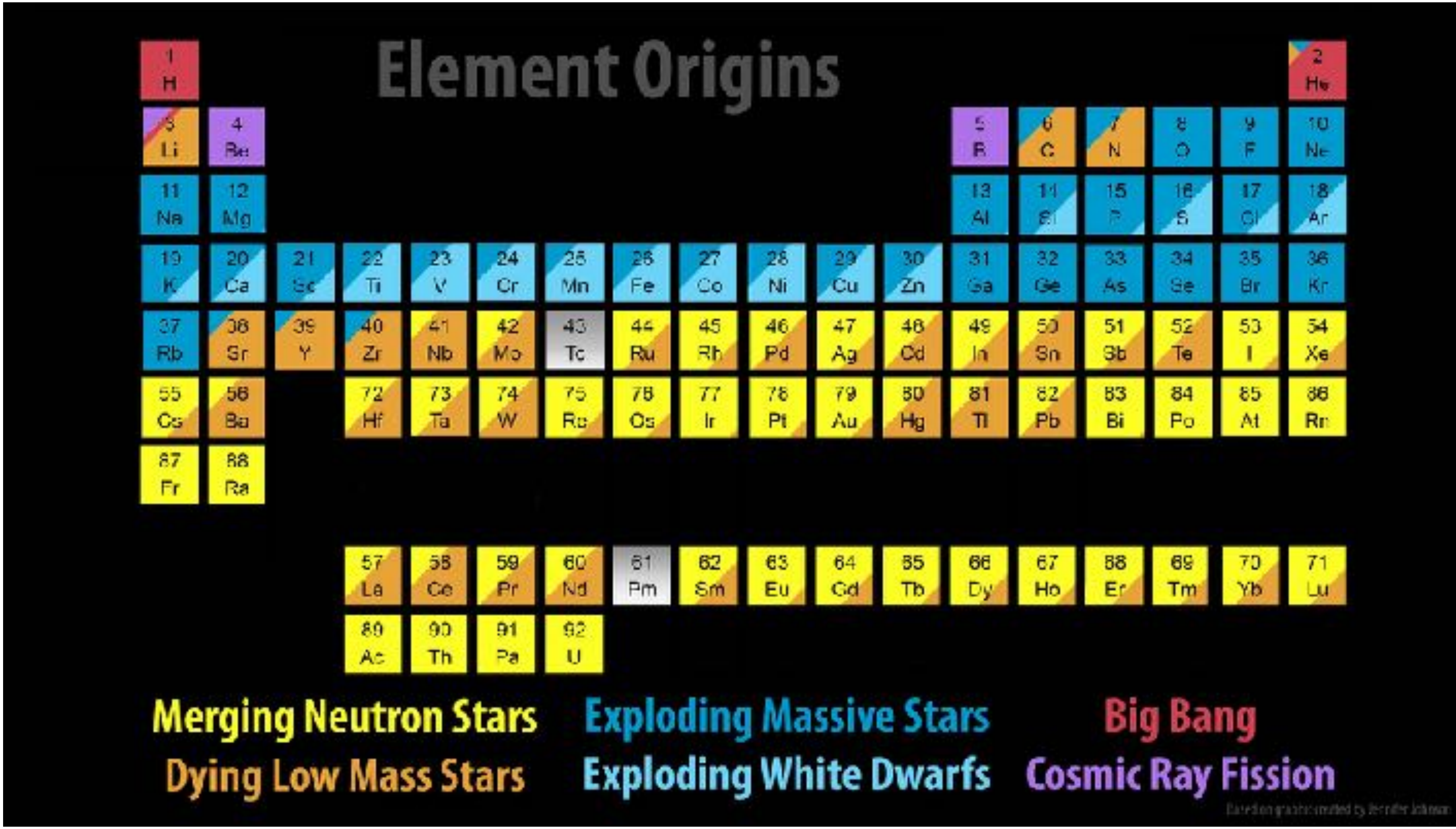


Credit: Metzger

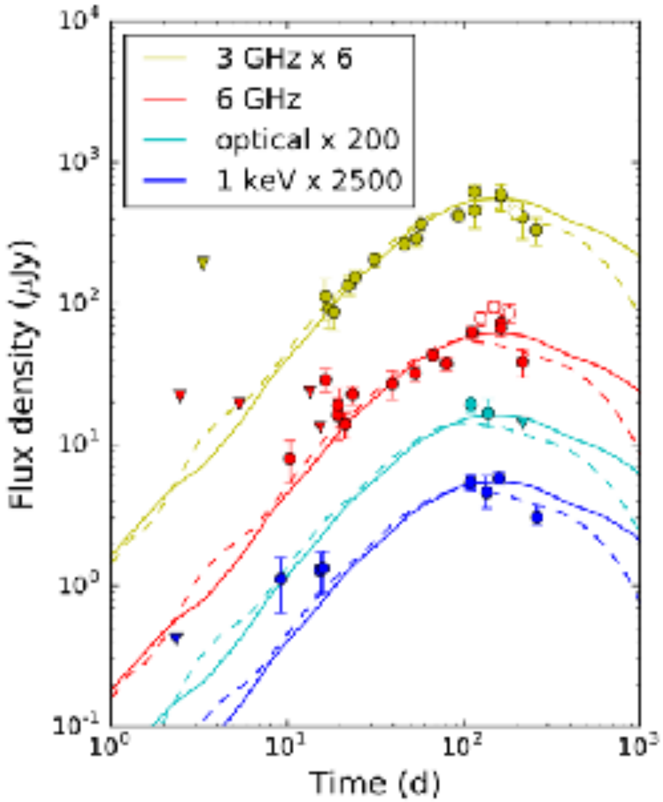
Kilonova Spectra



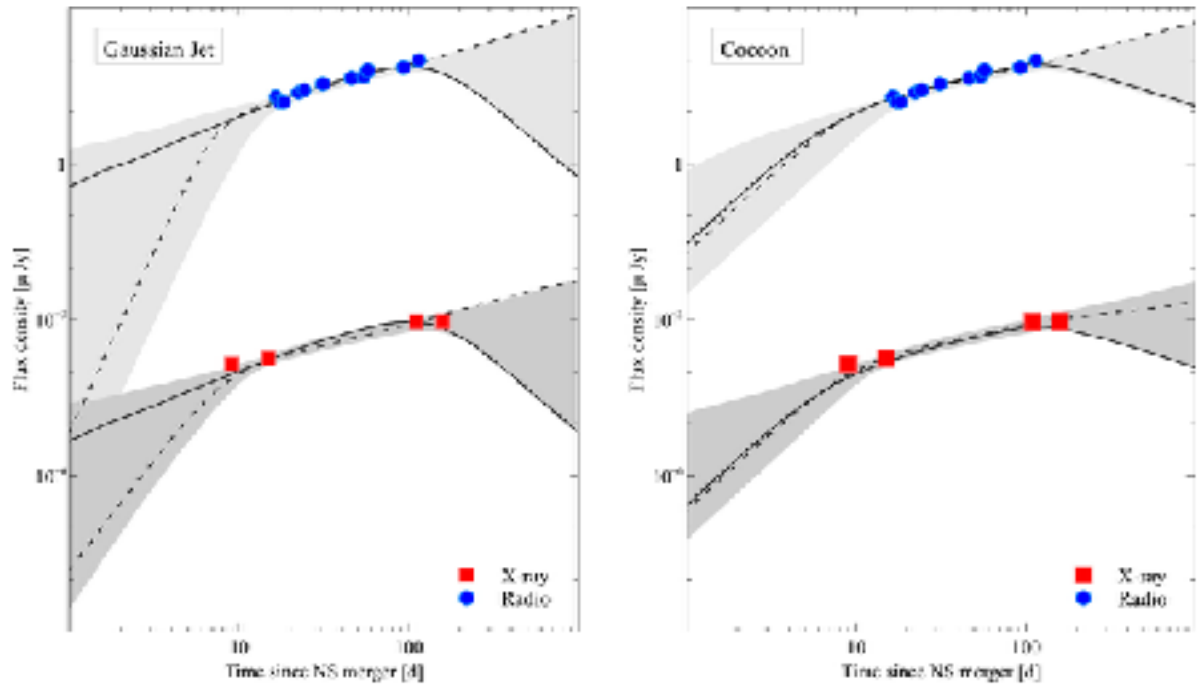
r-Process Nucleosynthesis



GW170817 - Late Afterglow



Alexander et al. 2018



Troja et al. 2018

See also Haggard et al. 2017

Follow-up to Neutrino Events

- Utilizes all search methods:
  - On-board triggers
  - Targeted search using event time (+/- 30s)
  - Untargeted search within the hour
  - Earth occultation technique (+/- 1 day)

- Upper limits published in GCN circulars
  - IceCube-171015A, GCN #22043
  - IceCube-170321A, GCN #20932
  - IceCube-161103, GCN #20127
  - IceCube-160806A, GCN #19817
  - IceCube-160731, GCN #19758
  - IceCube-160427A, GCN #19364
  - ANTARES 150901, GCN #18352

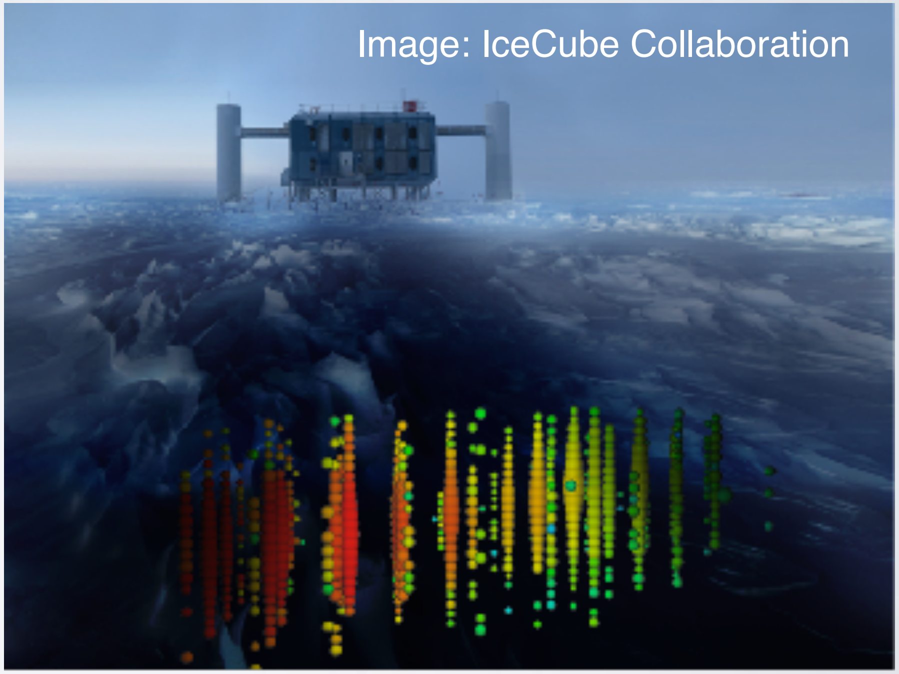


Image: IceCube Collaboration